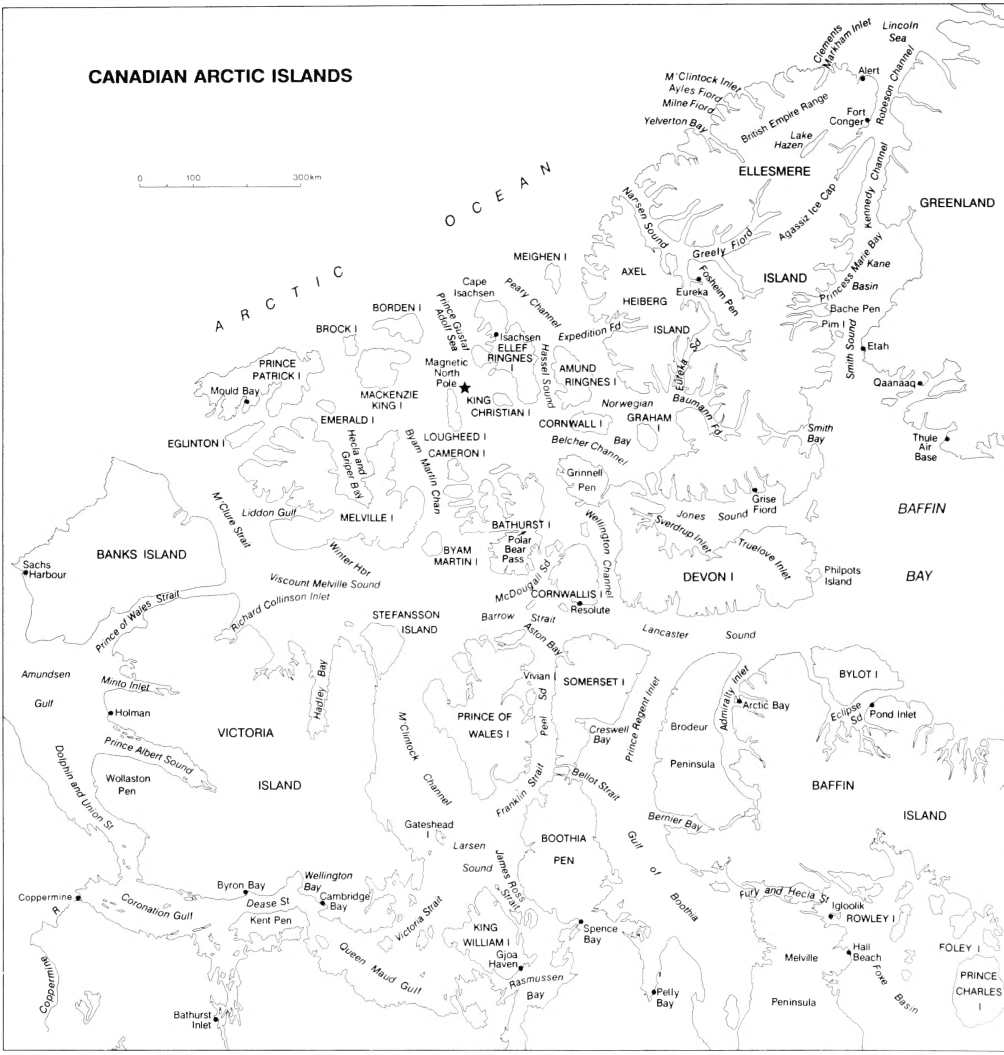
Canada's Missing Dimension

Science and History in the Canadian Arctic Islands
Volume I

Edited by C.R. Harington

Canadian Museum of Nature



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C.R. Harington

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INTRODUCTION

The engine droned on and island after island passed beneath the wing: masses of ice coiled like necklaces on the dark waters of the straits separating them. Basking seals popped into their holes like billiard balls as we descended. Circles of whalebone houses appeared, as common as moon craters, on Brooman Point en route to the lush arctic oasis of Polar Bear Pass (the only place I have seen a band of Peary caribou calmly drifting through a herd of grazing muskoxen). It was during a 1961 aerial survey of muskoxen and caribou in the Queen Elizabeth Islands that I first got an inkling of the vastness and diversity of the Canadian Arctic Islands. From the bleak, flat apron of the Beaufort Formation in the west to the badlands of eastern Prince Patrick Island, the fortress-like cliffs of eastern Cornwallis Island and intervening flights of raised gravel beaches, to the ice-covered mountains of Ellesmere Island with its spectacular tidewater glaciers and fiords.

I wish all Canadians could not only see, but experience life in the Arctic Islands. Although these islands comprise about a fifth of the country, and are significant and intriguing in their own right, they are Canada's missing dimension. Nevertheless, perhaps a few people not familiar with this region will gain a clearer picture of science and history there by consulting this book, which stems from an international meeting ("The Canadian Arctic Islands: Canada's Missing Dimension", sponsored by the National Museum of Natural Sciences, Ottawa, November 21-24, 1987).

Contributors to the book were encouraged to: provide current coverage of knowledge about the region's natural heritage; place that knowledge in historical context with a view to the future; detect important gaps in our present understanding of natural processes and suggest ways of filling such gaps. The following papers include a large sample of those presented at the meeting plus some pertinent new contributions.

The book begins with general discussions on support for, conflict in, and the future of scientific research in the islands. Following this, various spheres of knowledge are considered in sequence: (1) the geosphere (fossils - mainly vertebrates - and paleoenvironments); (2) the "hydro-cryosphere" (freshwater, sea and ice); (3) the atmosphere; (4) the biosphere (living plants, insects, fishes, birds and mammals other than people); and (5) the "anthroposphere" (human prehistory, history and recent expeditions). In some cases, the sections begin with general papers that will help readers gain perspective on the more specialized contributions - several of which will interest mainly experts. A natural transition between geosphere and "anthroposphere" sections occurs in A.J. Sutcliffe's paper.

This publication is intended for those who are deeply interested in nature, history and the Canadian Arctic Islands. It may be a handy milestone on our road to revealing the "True North" - perhaps complementing another recent Arctic Islands symposium volume (Zaslow 1981), which focuses more on the history of various disciplines, policy, strategy, sociology and economics.

A personal highlight resulting from attending the meeting and reading the papers was the potent combination of R.J. Conover and others' discourse on sea ice and its relation to biological oceanography with the National Film Board's "Edge of Ice" introduced by M.J. Dunbar. The paper and film revealed a whole new

upside-down world! While caribou, muskoxen, polar bears and humans use the frozen, windswept top of the sea ice as a bridge between islands or a hunting platform, there is a mellower, bottle-green world below: its faulted hills and valleys being the hummocky underside of the ice torn by bright leads. There, zooplankton graze like flocks of tiny sheep on greenish-brown fields of algae; and seals, like streamlined airships glide freely in three dimensions, navigating by the underice topography.

Several waves of human occupation have lapped the islands' shores over the last 4,000 years. Of these, the Thule people seem to have been most in tune with the environment. But even they were severely challenged by the deteriorating climate of the Little Ice Age - as were their Norse brothers, who apparently penetrated the eastern part of the region before their colonies in Greenland died out. During the last 400 years, Euro-American exploration using large ships and man-hauled sleds (surprisingly effective in a few cases), as well as Inuit-style dog-sleds, has led to the present situation. Now, settlements of Inuit and whites decrease in number and size northward to a handful of scattered weather/military bases like Alert that are serviced by aircraft or ice-breaking ships. Another characteristic is the bloom of fanatical scientists that flood the islands each summer, only to disappear during the most critical period for survival of the land biota!

Another impression I am left with is that this region has changed remarkably with time: from virtual tropical conditions in the Siluro-Devonian to arctic at present (only about 10,000 years ago most of the islands were covered by ice). Landscapes, plantscapes and animals changed in lingering harmony with the restless climate. What will the future bring?

How can we try to overcome the weaknesses in our knowledge of the Arctic Islands and begin filling the gaps so diligently indicated by contributors to this book? Why not establish several long-term, year-round "nature observatories" at inland as well as coastal sites and polynyas across the islands ...like a scientific DEW Line? They could focus on weather and climate as they affect biota (e.g. covering variations in aquatic primary productivity, plant productivity on land and swings in animal populations). Such observatories, fed by remote-sensing and automatic weather station data, would not only provide the earliest, most sensitive practical information on the biotic impact of the "greenhouse" warming predicted for the near future (should it occur), but would yield valuable insights into the long-term operation of arctic ecosystems. Such a move would strengthen Canada's claim to sovereignty in the region while developing arctic scientific expertise among northern native and other Canadian students. The essence of this proposal has been made many times (Hattersley-Smith 1982): perhaps, finally, it is time for action!

C.R. Harington, Editor

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SCIENTIFIC RESEARCH: SUPPORT, CONFLICT AND THE FUTURE

POLAR CONTINENTAL SHELF PROJECT

George D. Hobson[1]

Abstract: The Polar Continental Shelf Project (PCSP) was initiated by Cabinet Memorandum in 1958 shortly after Sputnik was launched by the U.S.S.R. PCSP conducts studies of scientific problems unique to the Canadian Arctic, and provides vital logistical support and advice to other scientific research groups working in the Canadian Arctic Islands and the Arctic Ocean. These logistics include equipment, a radio network, aircraft, base-camps at Tuktoyaktuk and Resolute - all the essential support to put scientists in the field, maintain them there safely while they collect data, and get them home again. It cooperates with government departments and agencies and with universities in providing expertise and facilities for their studies, and keeps both the scientific community and Arctic residents informed of continuing scientific operations. Visits to the settlements were begun in 1974 as a means of informing the native peoples about the science that was going on in their backyards; for years PCSP was the only contact some of the settlements had with scientists. PCSP's multidisciplinary, interdepartmental, interagency character continues to be instrumental in fostering effective and economical scientific development of the Canadian Arctic.

Résumé: L'étude du plateau continental polaire (EPCP) a été établie par mémoire du Cabinet en 1958, peu après le lancement de Spoutnik par l'URSS. L'EPCP étudie les problèmes scientifiques propres à l'Arctique canadien, et fournit les conseils et le soutien logistique essentiels aux autres groupes de recherche scientifique oeuvrant dans les îles de l'Arctique canadien et dans l'océan Arctique. Ce soutien logistique comprend de l'équipement, un réseau radio, des avions, des camps de base à Resolute et à Tuktyaktuk - tout ce qui est nécessaire pour amener les scientifiques sur le terrain, les y garder en sécurité pendant qu'ils y recueillent des données, et finalement les rapatrier. Elle collabore avec des ministères et organismes gouvernementaux, et avec des universités, auxquels elle fournit l'expertise et les installations indispensables à leurs études, et tient tant la communauté scientifique que les résidents de l'Arctique informés des opérations scientifiques en cours. En 1974, on a commencé à rendre visite aux communautés autochtones pour les tenir au courant des études scientifiques qui se déroulaient sur leur territoire; pendant des années, ce fut pour certaines leur seul contact avec des scientifiques. Le caractère pluridisciplinaire, interministériel et inter-organismes de l'EPCP demeure essentiel pour un développement scientifique efficace et économique dans l'Arctique canadien.

POLAR CONTINENTAL SHELF PROJECT

Of 40 papers presented at this international meeting on the Canadian Arctic Islands (many of which are included in this volume), only five were not supported by Polar Shelf. I am literally preaching to the converted. What can I say about Polar Shelf to such a group? First, I want to say something about its history, since many people do not know its background. I will also attempt to provide insight into how I feel about science in the North, and then I would like to mention something that is coming along. It is actually here now, but most of us have a tendency to ignore the land-claim settlements.

The Polar Continental Shelf Project (PCSP) was organized by the Advisory Committee on Northern Development (ACND). At present, that committee is moribund, but at one time it was very active. Some people attending this meeting, such as Jim Harrison, Graham Rowley and Keith Greenaway had talked about a Polar Continental Shelf Project for several years. They are the godfathers of the PCSP. By 1958, when a Memorandum to Cabinet

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was presented, these gentlemen, as members of the ACND, considered that the time had come for such a project. Although they were not pushed into the decision, they had a certain amount of assistance. Sputnik first flew in 1957. Also in 1958, the Law of the Sea Conference in Geneva stated that maritime states should have control over their resources. Canada, at that time, knew nothing about the resources on her continental shelves. The time had come indeed. Canada was nudged again because the Americans wanted to know the field of gravity in the Canadian Arctic. If you are going to fly satellites you must know the pull of gravity, and if the satellites are going to be in a polar orbit, you really should know what the gravitational pull is in the polar regions. So, there were compelling reasons to start such an agency. In 1958 a Memorandum to Cabinet established PCSP, and we were officially on our way. In 1959 our first party went to Isachsen on Ellef Ringnes Island to find out how one undertakes science in the Arctic and to learn the problems that had to be overcome to support science in that environment.

FIGURE 1: Polar Continental Shelf Project base camp at Resolute - an aerial view in April 1989.

Of course, Geological Survey of Canada parties had been active in the region previously, for example, during Operation Franklin in 1955 (Fortier *et al.* 1963), and

FIGURE 2: Hercules transport aircraft at Drake Point, Melville Island unloading a bunkhouse and fuel tanks for a seismic survey across Sverdrup Basin. Such logistical support is a major part of PCSP's role.

geologists such as Ray Thorsteinsson and Tim Tozer as early as 1947-1948 (Thorsteinsson and Tozer 1962; Tozer and Thorsteinsson 1964). But how does one do science on the fringe of the islands and on a much larger scale? There were eight people on that first party in 1959. Soon we were working from base-camps at Tuktoyaktuk and Resolute (Figures 1, 2), and by 1987 we had 235 parties asking for support. We estimate that there were probably 1,000 peaceful scientists in the Canadian Arctic in 1987 - and what better way to exercise sovereignty. In 1959 the budget was about $16,000; in 1987-1988 it was $5.1 million.

But we have had some highlights. In 1967 the former Dominion Observatory manned an expedition to the North Pole to study gravity and the deviation of the pendulum. In 1975 we undertook a joint operation with the United States in the Beaufort Sea, a period of 14 months in the project known as AIDJEX (Arctic Ice Dynamics Joint Experiment). In 1979 we had LOREX (Lomonosov Ridge Experiment; Weber 1989; Figure 3), in 1983 CESAR (Canadian Expedition to Study the Alpha Ridge; Jackson *et al.* 1985), followed by an ice-island project in 1983, when we boarded that "giant vessel" powerd by ocean currents.

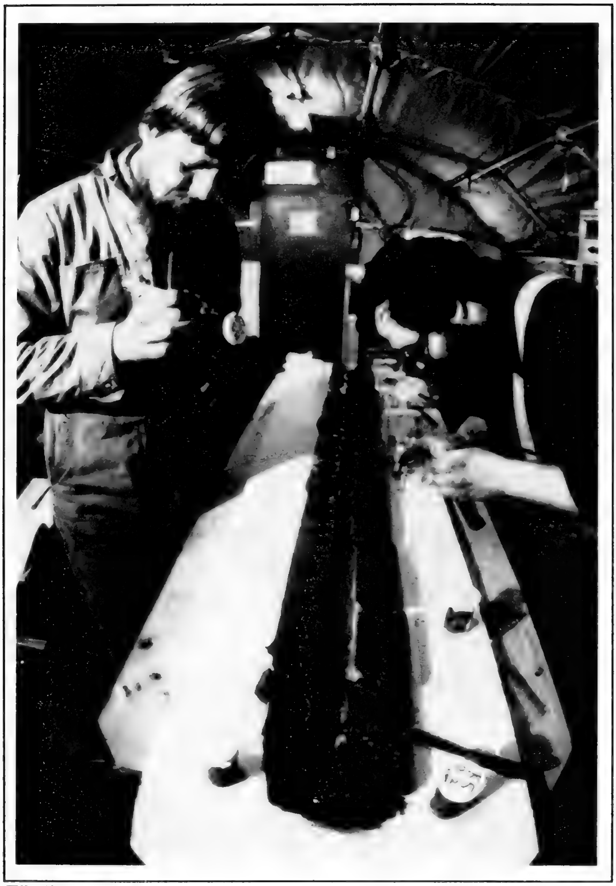

FIGURE 3: Steve Blasco (R) and Brian Bornhold (L) analyze a marine sediment core during PCSP's LOREX (Lomonsov Ridge Experiment) project in 1979.

At one time PCSP had a staff of 26 scientists, most of whom were lost to the rest of the department in 1967-1968. The last three scientists were taken from Polar Shelf in April 1986. Now we are completely dedicated to the provision of logistic support to science.

FIGURE 4: Mary Dawson (top) and Howard Hutchison (kneeling) collecting Tertiary vertebrate fossils in the Eureka Sound Formation near Bay Fiord, Ellesmere Island (see Dawson, this volume). The project was supported by PCSP.

We have had other highlights, such as participation in the discovery of a rhinoceros skeleton in the High Arctic (see Dawson, this volume; and Figure 4) and the discovery of the first dinosaur bone from the Canadian Arctic Islands (see Russell, this volume), all of which are exciting events. Indeed, this is perhaps where PCSP staff gets a lot of its satisfaction ... seeing scientists getting into the Arctic, doing their thing and doing it well.

At this point I would like to quote from Hansard of May 26, 1959:

> "The Arctic Archipelago, the Polar Ice Cap and Arctic waters are of vital economic and military significance. Large areas of sea ice may be used as airfields and semi-permanent bases for scientific or military

purposes. Submarines are capable of surfacing through the Polar Ice Cap and in open leads without detection".

"Development of similar latitudes in Russia shows a marked advance; so much so that the Canadian Government is placed in the position of obtaining most of its Arctic scientific knowledge from information supplied to us from time to time by the Russians."

"A scientific group has now been sent to the Polar Continental Shelf to study hydrography, oceanography, geology and other geophysical characteristics of the shelf and adjacent land areas. The expedition this year is in the nature of a reconnaissance. Because of the vital nature of the work being undertaken it is essential that this group be expanded by at least four times next year with steady increases thereafter. The scientific work on the Arctic Ocean Continental Shelf should be a continuing effort until the mineral potential and major features of the area are known. In a rapidly shrinking world our sovereignty in the North must be continually reviewed and strengthened. There is no more effective way, no means less costly, and no method intrinsically more useful, of strengthening our sovereignty in the North than by the conduct of thorough scientific field research programs and the publication of their results. The Polar Continental Shelf Project is one of such programs."

Have things really changed? Even in 1959 scientists working in the Canadian Arctic were being encouraged to publish. Indeed, PCSP has produced eight volumes of abstracts covering many such projects and publications supported by it (Hobson and Voyce 1974, 1975, 1977, 1980, 1983, 1985, 1987, 1989). Those are a few of the highlights of PCSP history.

Let's discuss some of the Arctic science policy today. As we can see, Polar Shelf was originally concerned with sovereignty. It was one of John Diefenbaker's visions of the North. What better way to exhibit, gain, maintain sovereignty than to have 1,000 peaceful scientists walking around the countryside (Figures 5, 6)? Scientists can establish Canadian sovereignty. Let us recall Norway and Denmark who argued over Greenland: Denmark sent its scientists to Greenland while Norway ignored the opportunity ... and who has Greenland today? We scientists *are* Canadian sovereignty. Canada's investment in science may have been one of the cheapest yet most effective means of establishing a sovereign base for our northern lands and seas.

Science in the North is conducted to meet three major Government purposes. The first one is economic and regional development, whether it is looking at the natural resources, or whether it is Health and Welfare Canada participating in the regional development of the settlements. The second purpose is to support government missions,

FIGURE 5: Fritz Koerner (L) and Lief Lundgaard inside a Parcoll hut taking an ice core from the Devon Island Ice Cap - a PCSP project.

FIGURE 6: Narwhal studies near Pond Inlet, Baffin Island, were also supported by PCSP.

whether it is national security, the safety and health of Canadians, the study of the environment, cultural development or just plain policy-making. The other, purpose for being in the North is to advance knowledge and the supply of highly-qualified people. But I have one criticism: the Federal Government, since the early 1970s, appears to have redirected much of its support for long-term, sustained research and systematic data-gathering to the resolution of urgent short-term policy and political problems associated with non-renewable resource development or surveillance for defence. Certainly, most scientists working in Canada's North would agree that there is a chronic shortage of funds to support polar research in Canada. There has also been a serious decline in the infrastructure that supports polar science.

Furthermore, polar science in Canada is not well coordinated - a fact brought out in the publication "Canada and Polar Science" (Adams *et al.* 1987). Each agency operating in the Arctic is autonomous. There are more than 20 government agencies, 34 or more universities in ACUNS (Association of Canadian Universities for Northern Studies), Provincial and Territorial government agencies, native development corporations, as well as individual and private organizations, in the North. All are trying to carry out this work. But who makes Northern science and research happen? Who identifies the need for Arctic research? The answer to these two questions is - *no one.* There is a need for pulling together all the pieces, and someone should identify the gaps in northern science. Perhaps the first recommendation in "Canada and Polar Science (Adams *et al.* 1987, p. 114) should be supported i.e. "... that a new, federally funded institution dedicated to understanding, funding or managing research in the Canadian North and the polar regions NOT be established at this time or in the near future". However, perhaps we do need an Arctic Research Commission - the second recommendation. There is a lack of cohesion, and no body other than the Federal Government in Canada has the capacity or the mandate to ensure that necessary research in the Arctic is undertaken.

The Colwell Report, recently released in the United States, urges that the National Science Foundation in the U.S.A. take the opportunity to integrate polar science into a broad, global, system-oriented program at the frontier and at the frontier of science. Another recommendation in the Colwell Report is that the funding for polar science be doubled. The Arctic Research Commission in the United States has reported to the

President, and there is a strong desire, at a high level, to increase the budget for science (U.S. Arctic Research Commission 1988A,B).

Let me go on to land-claims. I have been involved with some of the settlement claims, particularly those concerning COPE and Nunavut, and on the periphery of the Dené/Metis and Yukon settlements (Indian and Northern Affairs Canada 1985). Some of us have been impelled to face up to the rules and regulations of these settlements, and I think that we are all going to have to deal with those rules and regulations in the very near future. Nunavut is the largest claim in the country - land equal in area to the combined extent of Manitoba, Saskatchewan and Alberta. Also, consideration will be given to native peoples controlling the offshore area, which is in none of the other settlements. Therefore, we are looking at a massive area of Canada that may be controlled by native peoples. Some 16,000 native people will control a big part of our country, including much of the Sverdrup Basin - a good part of the land that you and I think they have never used for hunting or fishing. Some 17 sub-agreements have been signed, such as those pertaining to wildlife, access to the land, archaeology, national parks, etc. We are speaking about the balance between land-ownership and cash compensation in the arbitration process that is occurring. Both must be resolved. And they must be resolved with perhaps other considerations. The native peoples are going to get money as well as some 400,000 square miles (1,036,000 sq km) of land. It may be as much as 32,000 square miles (82,880 sq km) in the offshore. These numbers may not be exact, but at least they indicate that a lot of country is involved. And one of the things that the native people will want is *jobs*.

If you have been following the territorial situation, you will be aware that there is no party government in the Northwest Territories. A major problem facing that government is deciding how they are going to govern and be governed. Some people say that Nunavut means "our land". It is not the government's land. No treaty has ever been signed and aboriginal title and rights have never been relinquished. On the other hand, some would say that the North is government land. After all, government has been managing it for decades. We have two different opinions; that of the Inuit and that of the government. Can the land be owned by two different groups? That is why we have land-claim negotiations today.

In late September 1987, I attended the Alaskan Science Conference in Anchorage. It was interesting to sit in a workshop with a panel of three native people, and it was more interesting to hear what those native people had to say. I caution you that we should pay attention to what the native people are saying. At the individual and regional level, they must be involved in research. I can hear Arctic scientists now: "How can any native people plan my program?" But, native peoples must be involved in research. The local people want to decide what is going to be studied if it is going to affect them. For example, the people in Arctic Bay want to participate in a geological program, especially if it is going to result in discovery of another mine. They want to take part in our research design. They want to set the agenda. These are the words that have been used. They want to be involved from the start to the end. They should be consulted even in data-interpretation and surveys. Do I speak for Arctic scientists when I say that maybe we are just a little bit egotistical, and wonder how they can participate in the interpretation of our data? That's what they want, and that is it what you and I must be prepared to face. But behind that, they want to encourage their young people to get into science, they want to develop managers, to become involved. Past procedures must change. Native people are concerned that a lot of the research does not address local problems. They are not happy with the way we have gone into their backyards, carried out field work and returned south with our rock samples, with our artifacts, etc. They want a stake in their land and a say in how it is handled.

Another thing the native people want us, as scientists, to remember is that their cultural and religious backgrounds are different from ours. It is particularly important to recognize this when we undertake wildlife investigations. There is a spirit that you and I are seldom aware of; few of us have ever been involved in that part of their lives. Do we appreciate sufficiently their religious and social background? I would have to say "No". They want us to be sensitive. Sometimes a native will say "No" to us without explicitly using the word "No". They will intimate to us that they don't want something, and we don't listen to them because we have neither the social background, nor perhaps the sensitivity to clearly understand them.

Another prime consideration is that information gathered by scientists must get back to the settlements. How many of us have sent a map back to the settlements? How many have sent a publication dealing with their backyard? I think I may have hit a few nerves

here! Once I took a cardboard box of every publication we have in our library pertaining to the Tuktoyaktuk Peninsula to a Council meeting in Tuktoyaktuk. Although I don't know what they did with the information, at least they have it. How many of you have taken publications back to settlements in the vicinity of your field areas. I emphasize that native people not only want to know what is going on in their backyard, they have a right to know (Figure 7). These people are puzzled why they can no longer go into their backyards, or their flower garden, because it has been made into a national park. Why can they no longer hunt in certain areas? There is the perennial complaint that people in the North tend to be treated as objects of study, but never hear the study results. Soon, I believe that we will see the research priorities established by native boards who will not only make decisions about natural-resource management, but who will control the resources to develop native researchers and conduct studies on their own.


FIGURE 7: George Hobson (L) of PCSP. The role of scientific liaison with people in arctic settlements is important. Pangnirtung, Baffin Island, July 1988.

We must remember that people are a part of the ecosystem. We have to involve people in our studies and in the collection and analysis of our data. These people want to be involved and you and I, in the new era, will have to consider their needs. When the last claim is settled, they will own the lands in principle, the same as you own the land on which your house is built. For too long we have undertaken our research in their backyards without consulting them. Soon, we will be obliged to recognize that they own the land and want to participate in advancing scientific knowledge in the Canadian Arctic.

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Illustrated by Brenda Carter

CONFLICT IN NORTHERN ACTIVITIES

R.L. Christie[1]

Abstract: Conflict is inherent in competition between countries, organizations, and individuals, and the stress due to competition and conflicting goals has played a large part in the development of the Arctic. Early voyages of discovery were motivated by aggressive national pride and competition for commercial sea routes; sovereignty and strategic concerns among Canadians are attributable to conflict, or the possibility of conflict, between nations. Conflicting goals in modern development of the North have led to widespread disadvantage for native northerners. The conflict between the requirement of massive funding for mineral or petroleum exploitation in the Arctic, and the lengthy passage of time and the doubts in realizing returns, has been a continuing burden. Conflicting goals of adventure versus 'good' research in northern scientific studies, evident in the Canadian Arctic Expedition, 1913-1918, may still be with us. Conflict in goals is useful to the extent that people's wits are sharpened and there is improved awareness of interests and problems.

Résumé: Les conflits font partie de la concurrence entre les pays, les organisations et les individus. Cette concurrence et des objectifs incompatibles ont fait surgir des tensions qui ont joué un rôle important dans le développement de l'Arctique. Les premiers voyages d'exploration ont vu le jour grâce à une grande fierté nationale et à la compétition pour des routes maritimes commerciales; les préoccupations de souveraineté et de stratégie chez les Canadiens viennent des conflits ou des possibilités de leur émergence entre les nations. Dans l'actuel développement du Nord, des objectifs contradictoires ont entraîné, pour les autochtones du nord, de vastes désavantages. Les conflits entre les besoins d'énormes capitaux pour l'exploitation des minéraux et de pétrole dans l'Arctique, les longs délais et les possibilités douteuses d'arriver à des résultats positifs sont un problème continu. Les objectifs contradictoires entre les recherches scientifiques dites "hasardeuses" et celles qualifiées de "bonnes", qui sont apparus lors de l'expédition dans l'Arctique canadien de 1913-1918, peuvent être encore présents. Les conflits d'objectifs sont profitables dans la mesure où il faut travailler les esprits et améliorent la conscience des intérêts et des problèmes.

INTRODUCTION

A philosophical geologist, M.T. Greene (1982), remarked: ... "communion with nature is a prelude to battle with naturalists". This, and other observations, led me to the subject of this paper: that conflict has been and is inherent in our way of doing things. Conflict, in broadest terms, is part of the way humans operate; it toughens and often brings out the best in us. However, we are in fact trained to avoid conflict. Extremes in conflict are so obviously destructive - even life-destroying - that the reaction of our protective parents (notice that they are called 'guardians') is to attempt to turn us toward beautiful, soul-satisfying 'cooperation', 'love', 'friendliness' ... the lamb lying down with the lion, and so on. I do not discuss here nasty conflict, or armed conflict. For conflict read also competition, or stress. The motivation may be self-preservation, but the conflict I am concerned with is not at the level where the adrenalin is flowing.

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Anti-conflict moves can be productive, of course (e.g. a conciliation board, an ecumenical council, or cooperative projects). But the prime mover in each of these cases is conflict, or the threat or possibility of it.

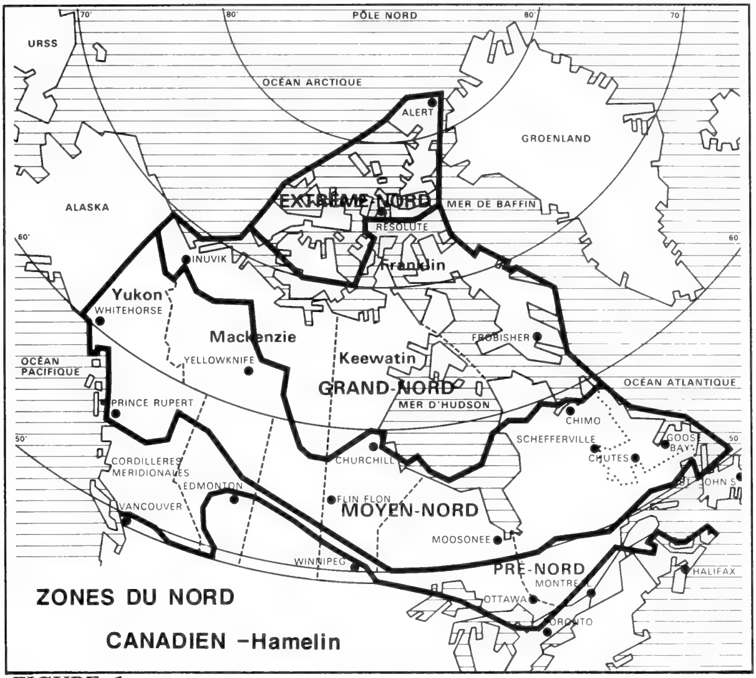

FIGURE 1: Zones du nord canadien (Hamelin 1970). In this map, Hamelin expresses degrees of 'nordicity', which incorporate various factors such as summer and annual temperatures, plant-cover, and accessibility from 'the South'.

The very idea of Man in the Arctic is an exercise in conflict, at least at first glance, and from our mainly southern perspective. Inherent in the expression: 'hostile environment' - so often heard of the North - is the concept of conflict. A view of Canada from the south is evident in Hamelin's (1970; Figure 1) illustrations showing 'nordicity'.

An American architect, in a recent Public Broadcasting System documentary, remarked that "... every house is, for its occupant, a private sanctuary and a public stage". You see in that the potential for conflicting goals: the house must satisfy at least two opposing needs, and a glance at a house often says something about the characters within. So, what do

outside viewers think of people who are of the North when they look at our house? How are the conflicts that are inherent in northern human activity balanced? If all is calm, and the lamb is nestled with the lion, then perhaps something is wrong; something is hidden. Either the lamb or the lion is putting on an act!

Let's look at five areas of activity in the North to see what conflict there has been, and where conflict occurs today. In doing so, we may discover the state of health of northern activities, or see what use the conflict can be. Undoubtedly, a deeper investigation than I am concerned with here would uncover a great deal more conflict. But this is a personal account, and I hope to create a positive view of the North.

HISTORICAL CONFLICT

The Canadian North is defined in political terms: from the outside in, rather than as native northerners would describe it (it was, to them, The World). The Canadian North is the product of periods of competition. First, the English and Dutch commercial adventurers (from 1553) sought alternatives to southern sea-routes around Africa and around South America, which were discovered and controlled by the then dominant maritime powers, Spain and Portugal. Following the Napoleonic wars (ending 1815), Britain supported geographic exploration in competition with Russia. The British-Canadian North was bounded on the west (as Canada is now) by Alaska (Figure 2), a huge land that was the subject of areal and boundary discussions and disputes between 1821 and 1825.

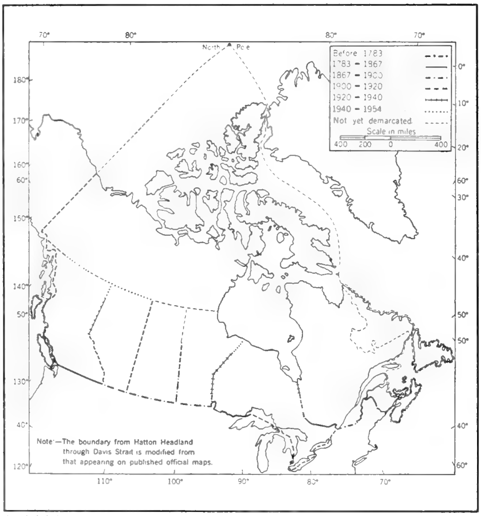

FIGURE 2: Map showing the stages of delineation of boundaries of and in Canada (Nicholson 1954, p. 98).

(The disputes were finally settled between the United States and Canada in 1903, the Americans having purchased Alaska from Russia in 1867) (Nicholson 1954; Sollie 1983).

Sometimes places in the Canadian North can be identified from reading historical accounts, or even from the character of current geographic names, with various European countries. The Sverdrup Islands and southern and western Ellesmere Island - Norwegian "New Land" - immediately come to mind. Americans left their mark in northern Ellesmere Island and some southern whaling areas, and in fabulous "Crocker Land". The point is that national loyalties and international competition played their parts in the opening of the North. Never did this amount to warlike behaviour - Robert Peary refusing to stop for coffee with Otto Sverdrup (1904, Volume I, pp. 57-61) is all I can remember! The effect of such competition was wholesome: these men were striving to achieve more than personal goals.

Much of the archipelago was explored by British sailors in a massive search for their missing countrymen - Sir John Franklin and his crew. This achievement, also, to a great extent, was a consequence of national pride.

CONFLICTS IN NORTHERN POLITICS

Many conflicts present themselves: Canadian sensibilities over sovereignty vs international maritime rules; the strategic, international importance of the North vs our southern preoccupation with economic and military problems in areas where most of the people live; conflict between those who care about wildlife, or depend upon wildlife, and others who may have national or private commercial interests (e.g. Greenpeace vs the whale hunters); the conflict between northern pragmatists, the people who live, work, earn a living in the North, and the academics and idealists in the South. I could go on: books appear regularly on these topics.

Canadian Sovereignty and the North-West Passage

Although some British sailors walked part of and sailed the rest of the North-West Passage in the 1850s, it was a Norwegian, Roald Amundsen (1909), who first navigated it in the *Gjøa* in 1903-1906 (Figure 3). That was well after the Far North had been given over, at least in a major part, by Britain to Canada. The *St. Roch*, commanded by Henry Larsen of the Royal Canadian Mounted Police, sailed through the Passage in both directions in the 1940s (Larsen 1958). Whatever the history and the legal arguments, Canadians have taken the Passage, and indeed, all the magnificent channels of the archipelago as their own: they have been traversed by trading ships and government maritime patrols for decades. Also, it may be important in future judgements that the channels have been travelled as a matter of course by land-based people such as hunters and scientists, the frozen channels essentially becoming, albeit seasonally, one with the land (see, for example, Miller, this volume).

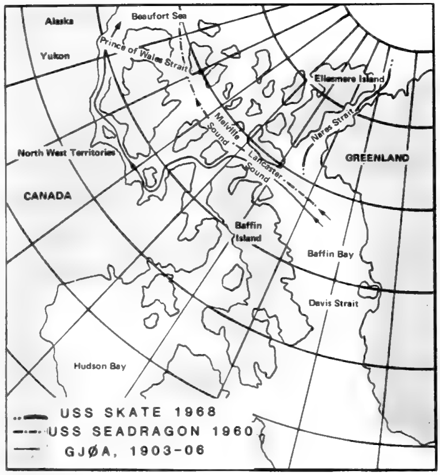

FIGURE 3: Map showing some ship and submarine traverses of the North-West Passage, as well as the more northerly route of U.S.S. Skate. (Bach and Taaghold 1982, p. 43).

At present, this conflict has yet to be resolved. There exists between Canada and the United States an uneasy tension: continental cooperation achieved in many areas on the one hand, but unresolved disputes, including the question of ship-transit through the archipelago, on the other (Vanderzwang and Lamson 1986).

STRATEGIC IMPORTANCE OF THE NORTH VS OUR COLLECTIVE PREOCCUPATION WITH SOUTHERN AFFAIRS

First, consider that military conflict, or its potential, has led to important advances in the Far North: the building of a travel and communication network of airports, weather stations, radio and radar systems, and, through advanced technology, the ability to travel and work at almost any time and anywhere in the North.

Military conflict of the Second World War led to the construction of the Alaska Highway and the Canol Pipeline and Road. Postwar fear of conflict resulted in the building of the Joint Arctic Weather Stations (JAWS), Thule Air Base in northwestern Greenland, and Distant Early Warning (DEW) Line stations.

FIGURE 4: The Soviet nuclear-powered icebreaker Arktika (later Brezhnev) reached the North Pole in 1977.

Advances in marine science and the potential for military conflict have led to great progress in northern hydrography, sea-bottom studies, marine geology, and oceanography. The High Arctic, once safe to ignore as more or less inaccessible, is now part of the modern world. The Soviet icebreaker *Arktika* (later *Brezhnev*) (Figure 4) reached the North Pole in 1977, as did the *Sibir* in May 1987.

Station Nord, in northern Greenland, was supplied by the icebreaker *Ymer* in 1980. Nuclear-powered submarines have been travelling our Arctic channels who knows how long or how often? The American submarine *Skate* crossed the North Pole in 1968. The recent location and exploration of the *Titanic* is but another step in man's increasing ability to travel and work in strange and forbidding parts of the globe.

These developments and activities are ‘advances’ from a southern perspective but may be of dubious value to some northerners, who see their way of life threatened or destroyed, and their basic sovereignty and dignity placed in doubt. Danish writers on strategy, Bach and Taagholt (1977, 1982), conclude that to ensure sovereign rights in Greenland (in light of the need for defence cooperation with the U.S.A. and North Atlantic Treaty Organization), Greenland/Denmark must cooperate and keep all sea and air-routes open for all nations; in other words, avoid conflict.

Wildlife

The conflict between Canadian and world sensibilities about clubbing newborn seals and the commercial gain from the activity is now part of history, and as we know native seal hunters throughout the North have been inadvertent victims through the depression of prices for all seal pelts.

A contemporary battle between the Greenpeace organization and the whaling industries of certain nations, especially the U.S.S.R., Japan, and until recently Norway, is still being fought. This battle is on a global scale, with widely - scattered skirmishes (e.g. whalers, described as ‘bandits’, were filmed in northeastern Asia, and a whale-conservationist protest took place in Brighton in 1983 (Anonymous 1983)). An advantage of the continuing conflict between the conservationists and the whale-exploiters is that the former are reliable, if not always likable watchdogs. They provide interesting facts about the activities of large-scale hunters such as those of the national whaling industries.

Close to home is the conflict between the proposed Arctic Pilot Project (APP), and the Inuit of Canada and Greenland. The APP would be an invasion by large ships to exploit northern hydrocarbon resources. On one hand, private operators hope to make a profit, and on the other, hunters wish to have their resource undisturbed (and unsoiled). The Inuit declare that the tankers are too noisy: not even the clatter of snowmobiles is allowed in Greenland (Anonymous 1980, 1982; Figure 5)!

FIGURE 5: An artist's drawing in Greenland Newsletter of a LNG (liquid natural gas) carrier, with a protestation against engine noise (Anonymous 1982).

Pragmatists vs Idealists

The northern pragmatists are the local people, including hunters, prospectors and transportation workers. They wish to live, to survive, and their goals are immediate financial and physical well-being, as well as local autonomy. Outsiders tend to want to control some of their activities: world concern for polar bears, for example, resulted in imposition of local quotas on these animals in our northern settlements (Davids 1982, p. 120). A little farther south, those who harvest game for meat, or fish, tend to want to eliminate supposed competing predators such as wolves or seals. Other people, acting as watchdogs, take the side of the predator, so we have a hearty conflict, again.

Native people like to bring down fat geese by shooting them on the wing; lawmakers on occasion insist that the natives obey southern hunting restrictions. This is a conflict between advancing population and development from the south and values that native northern peoples consider are essential to their culture.

CONFLICT IN THE SOCIAL DOMAIN

Invasions from the South

The Arctic, from a southern perspective, is a frontier; an alternative view is that of a homeland. Socially, southern movement into northern areas is an 'intrusion'. The economic goals of southern industry are in conflict with both the earlier and later social styles of the region, and are often even in conflict with social goals of the southern, or central government. The effects that the dominant, industrialized societies have had on the economic and social development of the northern peoples have been dramatic, and the conditions in the North have much in common with those of 'third world' countries (Griffiths 1983). The histories of the North, however, have differed from place to place. Griffiths graded northern native groups according to perceived degree of self-determination and, presumably, ability to carry on in their own life-style as follows: (1) Soviet Arctic peoples; (2) Sami (northern Scandinavia); (3) Greenlanders and Alaskan Inuit; and (4) Canadian Inuit.

The present condition of the Canadian Inuit was regarded (Griffiths 1983) as 'colonial', or of the lowest status.

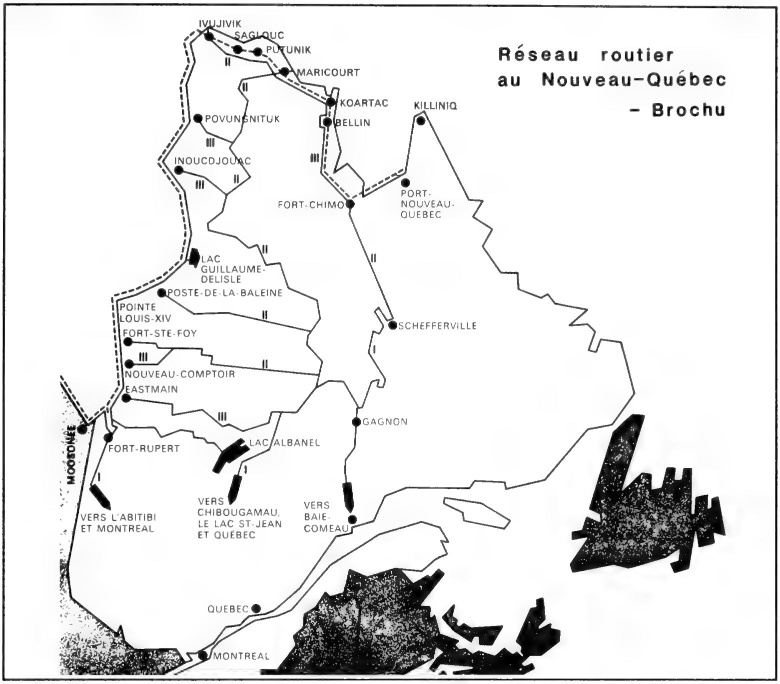

FIGURE 6: A proposal for a network of roads and winter-roads for Nouveau-Québec (Brochu 1970, p. 29).

Southerners going to the North, since the times of the earliest invasions, have had problems in adapting. They created their own problems to a great extent, and Vilhjalmur Stefansson throughout his career elaborated on this. Today, as ever, southern technocrats see problems in the isolation of industrial complexes in the Arctic, and workers often spend a number of weeks 'in' and almost equal time 'out', with the attendant problems, danger, and high cost of travel. The alternatives of integration with existing communities, or of training northerners, with their different work ethics and social values, are continually being considered. So far, little has been achieved.

The view of the North as a frontier, complete with an 'invasion' philosophy, can be seen in a proposal (Brochu 1970) for a network of roads for Nouveau-Quebec (Figure 6): this Réseau-routier has all the character of the tracks of a Panzer division.

Consider housing. The traditional Inuit house, or *iglu*, was open-plan, with an extended family or more than one family, living in it. Our intrusive society encourages one family per house, and the house is divided into rooms. The aboriginals did not claim ownership of land, or of unoccupied houses; the intrusive society, however, requires ownership and an investment of money. The resulting commitment is in conflict with the independent, nomadic urges of a basically hunting and travelling people.

Social conflict in different parts of the North has varied enormously. The contrasts in the social histories of Greenland, Arctic Canada, and Alaska (Sugden 1982), are reviewed below.

Greenland

Greenland was kept 'closed' by Denmark between 1721, when Hans Egede arrived, and 1948, when the Greenland Commission of that time recommended change from a colonial status. The Greenlanders, during this long period, were shielded from world trade; a hunting life was maintained, with gradual movement toward a more commercial style through selling part of their catch. Then, during the Second World War, in which Greenland fell under the protection of the U.S.A., new outlooks arose.

After 1953, two elected members of the Danish parliament were sent from Greenland. Transportation, schools, and health-care were promulgated and by the late 1950s Greenland's population was increasing annually at 4%. A Greenland Committee of 1960 declared a policy of wholesale investment, concentration of population in existing, larger urban settlements, and development of the all-season marine fisheries as a mainstay of trade. Four open-water fishing towns grew explosively, and investment in boats, processing plants, technical schools, and utilities soared. Danish language was emphasized in schools, which were re-oriented toward an industrial society, and skilled workers poured in from Denmark.

However, by the 1970s there were in effect two Greenlands: large towns with many opportunities and high standards of living on one hand, and shrunken or abandoned,

peripheral villages with subsistence living and rudimentary services on the other. Sons and daughters migrated to the large centres. Social demoralization grew; the emphasis on Danish and the presence of so many highly-paid Danes led to alienation. Drunkenness, violence, suicide, and political protest arose.

A key factor in the developing dissatisfaction was a decline in the cod catch in the mid-1970s, despite an improved fishing fleet. With the main economic base weakened, Danish policy shifted back to a more country-oriented style and the number of resident Danes was reduced. Greenlandic teachers were encouraged, and home rule was achieved in 1979.

The crux of the problems in Greenland was the conflict between industrial, economic, and social goals of government and people. The social problems outran the attempt to achieve self-sustaining economic growth.

The Canadian Arctic

Canada's Arctic, in marked contrast with Greenland, has been dominated by laissez-faire, and has been open to world exploitation of resources. The original, self-sufficient Inuit communities were extensively invaded by American and British whalers in the 1860s, with devastating impact. The Inuit gathered at ship wintering-sites, game was cleared, and when the whaling industry collapsed (by 1907), Inuit populations were decimated by starvation and epidemics. A second economic boom, that of fur-trading with the Hudson's Bay Company, grew after 1910 and lasted until the late 1930s. This industry again concentrated the population in small centres, this time consisting usually of a trading post and a Royal Canadian Mounted Police detachment at least, and introduced a cash economy and many southern goods. During and after the Second World War, with the development of air bases (e.g. Frobisher Bay), weather stations (JAWS), and the DEW Line, a communications and air-route infrastructure grew.

The rapid construction, largely financed and carried out by United States-dominated operators, inspired a wave of social concern among Canadians; and hospitals, medical programs, and schools appeared. A widespread housing program was begun, Inuvik was created as the hub of the Mackenzie Delta region, and Inuit cooperatives were encouraged.

A fourth wave of activity followed the discovery of the Alaskan Prudhoe Bay oil field in 1968. Between 1970 and 1975, some $500 million was spent on oil exploration in the Beaufort-Mackenzie area and the Canadian Arctic Islands. Lead-zinc, copper, asbestos, tungsten, and nickel mines opened.

The development of the Canadian Arctic has been a typical colonial enterprise: long north-south transportation links to the peripheral resource area, with the resources often going directly overseas and investment commonly being foreign or multinational. The conflict lay between short-term development by outsiders and the social goals and well-being of residents. The economic benefit of this exploitation has been of short duration and in some cases of doubtful value.

Canadian Inuit were largely ignored in several of the developmental rushes, and to a great extent lost their distinctive way of life. The centralizing effect of stores, missions, schools, and administrators resulted in local overhunting and increased dependence on welfare. Children were educated in a non-native culture, yet were unable to compete with the intruding people for jobs. Loss of traditional values and prestige resulted in a downward, demoralizing spiral.

However, in Canada, as in Greenland, native and other sentiments were aroused, and more local autonomy and land ownership or rights were demanded in the 1970s; now they are being achieved. A new style of development may be arising in Canada: some mining and petroleum operations are treated as temporary projects connected to the South and are separated from the northern, permanent infrastructure, which focuses more on the Inuit. This is in contrast with the Greenland style, in which postwar economic and social policies and developments are integrated.

Alaska

In Aleut, Alaska means 'the great land' - it is an apt description. Before the historical invasions from the outside, Alaska was home for some 62,000 native people, including Aleuts, Inuit, Athapascans, and other tribes in the southeast. They lived in small villages. Alaska underwent five main intrusive waves between the early 1700s and the present.

From the 1740s, Russians quested for fur seals and sea otters in the Aleutian Islands, with peak activity between 1770 and 1867. The Aleut population decreased from 16,000 to 2,000 by 1840, and the village social structure was destroyed. This decimation was accomplished through forced migration, enslavement, and disease.

Whalers arrived in 1847, and in the course of this exploitation Inuit villages of the west and north coasts were devastated by disease. Whales - the basis of livelihood for the aboriginals - were much reduced in numbers, and the late 1800s saw wholesale starvation among the Inuit.

In 1869, gold was discovered at Nome, but the deposits were rapidly exhausted. Gold was found at Fairbanks in 1906, however, and became an economic mainstay until the Second World War. The native population of Alaska stabilized at about 30,000 following the decline that had taken place throughout the 1800s.

A fourth invasion, during the Second World War, was a friendly one by some 152,000 troops. Concerns over possible (and, in fact, an actual) Japanese invasion, and later about Soviet intentions, resulted in: (1) the rebuilding of the Anchorage-Fairbanks railway (built during an earlier boom); (2) construction of the Glenn and Alaska highways; and (3) the building of airfields and DEW Line stations. By 1952, 52% of the labour force in Alaska was on the military payroll.

An oil boom followed the discovery at Prudhoe Bay, on the North Slope. Oil had been found in 1957 on Kenai Peninsula, where production commenced in 1960. However, the Prudhoe Bay field was a quantum leap in petroleum terms.

Alaska, (like Canada's Arctic), has basically a colonial pattern, with coastal cities and inland centres peripheral to the large southern gateway, Seattle. A major difference, however, was the scale of the economic waves. Vast numbers of 'mainlanders' invaded the Alaskan territory (in 1959, a state), settling in a relatively agreeable land, and lending dynamism to the region. The American frontier ethic created an environment of unfettered capitalism. Economic exploitation was more than an opportunity to be grasped; it was a duty! However, economic goals eclipsed social goals: the immigrant population prospered at the expense of the native people.

The late 1970s witnessed a remarkable development. Life for Alaskan Inuit shot from a struggling existence to a position of strength. Oil property-taxes and royalties were spent locally to achieve native Alaskan social and economic goals. The 1971 Alaska Native Land

Claims Settlement Act, in effect, created a form of statehood for native Alaskans (cf. Hobson, this volume). The act was the culmination of several forces, including the recognition of the widespread disadvantage of native people, and the economic and strategic need of the United States to develop North Slope oil with minimal delay.

CONFLICT IN ECONOMICS

The basic conflict in the North is the same as elsewhere: the rush to make money vs quality in development and use of the region. This is another side of the conflict between the frontier and the homeland.

A potential example is the proposed park on northern Ellesmere Island. Substantial income is possible for certain northern operators, at thousands of dollars per tourist (and there were about 70 in the summer of 1987, though the park was not yet formally established). But how many visitors can the land stand before it is over-used and degraded, or the very solitude that is so valued by the visitor disappears? This problem, faced many times in more populated areas, has already been considered by people of Canada's territories (e.g. Butters 1973).

Another economic conflict in the North lies in the enormous cost of development vs the expected return on the money expended. Development (e.g. petroleum development) may have to wait for 20 years or more for financial returns. The amounts, and the interest charges on the amounts, boggle the mind. In the Arctic frontier, the financial return must be the more certain, or of greater value, or possibly the development must be of greater strategic importance.

The moral, demonstrated by the Alaskan experience, is: conflicts with northern people must be recognized and we must come to come to a mutual understanding so that long delays can be avoided.

CONFLICTS IN SCIENCE

Several areas of conflict, some wholesome in nature and others less so, can be noted: (1) the historical conflict between the colourful adventurer and the plodding scientist; (2) the rush for 'empire' (territorial or scientific), at the expense of good work and progress; and (3) conflict between the demands of time and resources for teaching vs research.

The conflict between adventure and science has been with us for a long time. The early travellers were all adventurers at heart, even if the excuse for travel at the time was national pride, territorial gain, or even science. Think of Roald Amundsen, a true Nordic adventurer, feeling obliged to learn a useful bit of science (in his case geomagnetics) so that he could justify and raise support for his adventures. It was pretty thin support: on one occasion he had to get under way surreptitiously to avoid creditors who were about to seize his ship! Today, real adventurers can climb mountains or cross the Arctic Ocean, either using their own resources or raising money through promises to publish books or newspaper articles. But even today the old idea reappears that it is more respectable, or supportable, if a little 'science' is done (see Cochran, this volume). Perhaps, however, when you get down to it, institutional scientists are nothing more than closet adventurers masquerading as scientists!

One of the more notorious clashes between adventure and rock-steady science in Arctic Canada occurred during the government-sponsored Canadian Arctic Expedition. The Director of the Geological Survey of Canada in 1913, when the expedition departed, was R.W. Brock, a man who had guided the Survey to its present tradition of high scholarly and scientific standards. The Survey had assigned several field men (J.J. O'Neill, K. Chipman, J.R. Cox, and G.S. Malloch) to the project, and they were to be directed in the Arctic by R. M. Anderson, who had been a companion of Stefansson in earlier work. A regular, systematic scientific program was envisaged. This approach, however, contrasted with the more dashing one of Stefansson, whose style was to travel widely, live off the country, and be guided by the migrations of natives and game. A great setback occurred when the main expedition ship, the *Karluk*, was lost. Stefansson's determination to carry out his planned northern exploration in spite of the loss of people and materiel resulted in considerable tension among expedition members in the field. In the end, both Stefansson's

and the scientific goals were achieved, but at the expense of years of controversy and bitterness following the return of the expedition in 1918 (Zaslow 1975).

One expedition, however, that did combine the best of adventure with the best of science was Sverdrup's voyage aboard *Fram* into the Arctic Islands. The tough Norwegian crew travelled prodigiously for several years, had many adventures and saw much "New Land", at the same time accomplishing a great deal of science. The geological results alone put the expedition in a rank by itself, not exceeded until modern times and helicopter-supported projects (Dawes and Christie 1986).

The conflict between university teaching and research roles is necessarily blurred at more advanced levels of study, as the student and teacher collaborate in useful work. A traditional feature of the Geological Survey of Canada is worth noting: the hiring of junior and senior students as assistants for field work provides invaluable field-training and experience. This is usually an example of cooperation, except for rare occasions when the roll of the dice results in a totally green, accident-prone crew that puts an end to all hope of success. Then we have conflict!

An interesting aspect of conflict in science only occasionally applies to the North: the conflict between directors of science and the working scientists. A working scientist, typically an outstanding one, rises to direct his peers and discovers that the pressures and responsibilities of his new role are added to the earlier, habitual pressures of a scientist. Should he or she be a 'nice guy' or a 'driver'? W.A.S. Sarjeant (1986), in a book review, noted that "... it is the tyrannical and unloved Directors [of the British Geological Survey] who achieved most in research ... whether personally or through the work of their minions". Think about it!

CONCLUSIONS

Generally speaking, healthy, hearty conflict in the North is good for all concerned. It keeps us awake, and keeps us (more or less) honest because the conflict creates what can be called 'noise', and others become more interested in what is happening.

Is the situation altogether too calm in our North? I think not: both continuing and new conflicts are evident, as described here. Furthermore, I think we should carry on as we are doing, with a little conflict here and a little cooperation there, all with spirit and in good humour!

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Illustrated by Brenda Carter

SCIENTIFIC RESEARCH IN THE CANADIAN ARCTIC ISLANDS - THE FUTURE

E.F. Roots[1]

Abstract: The Canadian Arctic Islands (the northern fifth of Canada) present a remarkable diversity of natural phenomena, some unique features and a surprising richness in human history. The main driving forces for research in these islands appear to be: defence and sovereignty, environmental protection, resource development, social and political development, and global scientific questions often leading to participation in major international research programs. New research techniques (e.g. remote-sensing and automatic instrumentation) can be expected to find early use in the Arctic Islands, where study areas are hard to reach and field expenses are high. Scientific studies in the region are shifting from descriptive observations to research on processes, and causes and effects of observed phenomena. In future there will be greater emphasis on multidisciplinary, internationally-related research. If certain challenges to scientific progress can be overcome by long-term solutions, then rather than being "Canada's missing dimension", the Arctic Islands will add an extra dimension to science in Canada.

Résumé: Les îles de l'Arctique canadien (le cinquième du territoire) présentent une remarquable variété de phénomènes naturels, des caractéristiques uniques et une richesse insoupçonnée en vestiges de l'histoire de l'humanité. Les principaux moteurs de la recherche dans les îles sont : la défense et la souveraineté, la protection de l'environnement, la mise en valeur des ressources, le développement social et politique, et des préoccupations scientifiques globales impliquant souvent la participation à d'importants programmes de recherche internationaux. Les nouvelles techniques de recherche (comme la télédétection et les appareils automatiques) trouveront leurs premières utilisations dans les îles de l'Arctique canadien, où il est difficile de se rendre dans les zones d'étude et où les expéditions sont onéreuses. Les études scientifiques dans la région s'éloignent des observations descriptives pour aborder la recherche sur les processus, et sur les causes et effets des phénomènes observés. Dans l'avenir, on s'attachera encore plus à la recherche multidisciplinaire de portée internationale. Si on peut surmonter certains obstacles au progrès scientifique, à la longue, les îles de l'Arctique ne seront plus la grande inconnue du Canada, mais au contraire ajouteront considérablement à nos connaissances scientifiques.

INTRODUCTION

The general reviews and the more specialized papers in this volume give a picture of the present knowledge and research projects in the Canadian Arctic Islands in a wide range of scientific fields. These contributions show that although there are many distinctive aspects to research in the Far North of Canada, scientific knowledge about the Arctic Islands is nevertheless an integral part of the organized knowledge of all of Canada and indeed of the world. Seen in this light, the Arctic Islands present a remarkable diversity, some unique features, and a surprising richness.

No one who studies the Arctic Islands can fail to be impressed by the *diversity* of natural phenomena and in northernmost fifth of Canada, the *uniqueness* of many of its characteristics, on land, in the surrounding waters, and in the atmosphere; and the surprising *richness* of its human history.

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These papers embody the results of past research and discovery. And the history of that research and discovery is quite long. Although, as Robert McGhee (this volume) relates, people have been living in the Canadian Arctic Islands off and on for the past 4,000 years, our present knowledge derives very little from the knowledge of these earlier people. A remarkable awareness of the geography, including details of topography and oceanography, the environment and some aspects of the biology of much of the Arctic Islands is an integral part of the consciousness and the mental image of their surroundings of living Canadians whose ancestors have occupied the archipelago and northern mainland for the past 40 generations or so. But little of that awareness has passed directly to other Canadians who lived farther south in Canada, or whose forebears arrived more recently from other lands. Western man is undertaking research today to find out about the first human inhabitants of the Arctic Islands as objects of study, rather than building on *their* base of knowledge.

Except for the awareness inherited by those of us who are Inuit, our present formal ideas and understanding of the Arctic Islands appear to have begun with Leif Erikson about 1000 AD and by Karlsefni about 1010, who brought into European knowledge descriptions of Helluland (land west of Greenland characterized by smooth slabs of rock topped by a glacier). Probably Helluland is southeastern Baffin Island. The first representation of the Canadian Arctic Islands on a map, that we know about today, was drawn by Johannes Rysch of the Netherlands in 1507, who showed four islands west of Greenland and surrounding the North Pole. Rysch wrote on his map that he got the information from a book published more than a century earlier reporting Norwegian and English travels or legends. This information became widespread, and was included on several other maps, notably those of Lok, Ortelius, and Mercator, before Martin Frobisher in 1576 made the first documented voyage by a European to the Canadian Arctic Islands (Weber and Roots, this volume). Within the next 340 years the geography of the archipelago became fairly well charted; but it was not until 1947 that the last large islands, Prince Charles Island and Rowley Island, were added to the map, and in 1961 we made the last major correction to the map by moving Meighen Island to its proper location. So there is a long history of the gradual evolution of knowledge of the region.

I intend not to assess present knowledge or research, but to ask you to think about the future. Where is the present research taking us? What kinds of scientific problems

are emerging as the most important? Who will be doing the research in this area in the future, and what techniques will they use? And, very important, who will be sponsoring that research, and why?

The diversity and uniqueness of the Canadian Arctic Archipelago make the study of its natural features, its resources, and its history of great scientific importance and interest, not only for the understanding of the region for its own sake and its future development or protection, but also because understanding of the natural processes that occur there is important to world science, to many national issues, and to international relations. Modern study of the Canadian Arctic Islands has a significance that goes beyond finding out a bit more about a little-known part of the country.

If we are to consider the directions that scientific research in the Canadian Arctic Islands is likely to take in the future - in the light of the current research being described in this volume - we should step back from the detailed accounts of current scientific activities, and ask:

(1) What basic features make the Canadian Arctic Islands distinctive or scientifically important?
(2) What kinds of scientific problems are being addressed today? In which problems or subjects is our knowledge approaching maturity, and what new areas are emerging as high priority?
(3) Who is addressing these problems and why? What do the researchers hope to find, or to find out?
(4) What is the importance of the new knowledge being sought? To whom is it important?
(5) What other studies, in different regions, are important to our research in the Arctic Islands, and vice versa?

If we can think about these and other questions to get a mental picture of some of the important characteristics of the islands and the reasons for the present studies, we will have a better basis for speculation about future research.

BASIC FEATURES OF THE CANADIAN ARCTIC ISLANDS

This is not the place for a description of the geography or the scientific features of the Canadian Arctic Islands; but let me remind you of a few varied facts that may be important to an appraisal of where research in this complex area is heading, now and in the near future.

Geography

The Canadian Arctic Islands comprise about 20% of Canada's land area. If you include the islands in Hudson Bay, they cover about 30 ° of Latitude; a north-south distance roughly equal to the distance from Ottawa to Guatemala. Most of the islands, however, lie north of the Arctic Circle, in a triangular mass that, if it were transposed to southern Canada, would cover the land between Vancouver, Sault Ste. Marie, and Yellowknife. So we are talking about a large chunk of country! It is a country that ranges in scenery from flat, nearly featureless desert - Banks Island is my candidate for one of the most monotonous large pieces of land anywhere on Earth, not counting the interior of Antarctica or Greenland, to walk or ski across - to spectacular fiords and steep, glacier-hung mountains that attract enthusiastic mountaineers from all over the world (Cochran, this volume). Understanding, or even describing this varied land and the marine waters that cut through it and surround it, is a scientific challenge in itself.

Geophysics

The Arctic Islands contain the North Magnetic Dip Pole which is now somewhere off northern Bathurst Island and moving north a few kilometres each year. That's where the compass needle stands on end, as the lines of magnetic force are vertical. The geomagnetic pole, which is the north pole point of the magnetic field generated by the Earth spinning in space like a big magnet, is also in the Canadian Arctic Islands, on Ellesmere Island. These magnetic phenomena make the region especially important for geophysical and space studies (critical to planetary science and applied sciences ranging from communications to prospecting for minerals), which can be carried out nowhere else.

Environment

The high latitude of the islands means that solar energy is received at a low angle, and for part of the year there is no direct solar radiation at all. The net energy received from the sun at Resolute, near the middle of the archipelago, is only about one-seventh that received at Toronto. The results are familiar to everyone concerned with the Arctic: (1) low temperatures; (2) water on the surface, in the ground, in the air and in plant tissues is, throughout the year most commonly solid (ice or snow) rather than liquid (ordinary water or vapour); (3) most of the solar energy received in spring and summer is used to melt ice or snow, not to raise temperature (see McKay, this volume). In most of the archipelago, the lands or waters are only free of snow and ice and can begin to get warm and support life long after midsummer, so that growth can take place only while the sunlight is getting weaker and the days are getting shorter. Special forms and communities of life have had to develop to live under these trying conditions - on both land and at sea (e.g. see Connover *et al.*; Bliss; Danks, this volume).

Geological History

The Arctic Islands have not always had the global position or the environmental conditions they have now. They are migratory land masses. The presence of coal, petroleum, fossil coral reefs and dinosaur bones (Russell, this volume) testify to a different history and different climates in the past - and give a potential economic importance to the region that it would not have, had it always been as we find it today. As Mary Dawson (this volume) points out, at least since Tertiary times the islands have been in arctic latitudes; but for most of even that time the climate was more temperate than it is today. Not only did lower sea level produce a Bering Isthmus, but a milder climate gave many animals who do not now live in the Arctic something to eat as they wandered across this land connection.

Modern Changes

Although few people live on the islands today, they are by no means unaffected by modern human activities. The once clear air now carries a distinctive "arctic haze" whose origin is in industrial smokestacks in the temperate zone (McKay, this volume). Polar bears and whales in the archipelago carry in their livers chemicals that were sprayed on fruit

trees and cotton fields far to the south. Icecaps on Devon Island and Ellesmere Island (Koerner, this volume) faithfully record global pollution, year by year, and show the distinctive changes caused by industrial expansion during the present century. And all indications are that the rapid world-wide climate change, which may be expected during the next century because of accumulation of man-made greenhouse gases in the atmosphere, will have its greatest effect in the zone between 60 and 75°N - which includes most of the Arctic Islands.

Geopolitics

The Arctic Islands are the part of Canada facing the Soviet Union across the Arctic Ocean. Alert is almost twice as close (2,400 km) to the Soviet nuclear test-site on Novaya Zemlya or the ICBM silos on the Kola Peninsula as it is (4,700 km) to the North American Air Defense Command ICBM silos in North Dakota. Thus the geography of the Arctic Islands becomes a key element in global military and peace-keeping strategies. This situation, no less than the low temperatures or the potential petroleum deposits, is one of the basic features of the Canadian Arctic Islands today.

Results of Basic Features

The net result of basic natural conditions noted above is the diversity, uniqueness and richness that characterizes the Arctic Islands today: arctic weather; long polar summer days and long winter nights; the aurora; permafrost; vistas of prolific flowers in summer and wind-driven snow in winter; sea ice; icebergs off the east coast and ice islands in the Beaufort Sea. And low-energy ecosystems, short food-chains with remarkable adaptations of individual species and biological communities. Muskoxen; caribou; lemmings; arctic wolves; Snow Buntings and Snowy Owls; seals, walruses, polar bears. Oil, gas, coal and metals, although how much and whether the deposits are really worth anything in net economic terms may be uncertain. A short shipping-route between London and Yokahama; a short flying-route between Moscow and Los Angeles.

These are some features of the Arctic Islands today. All these are why the islands and surrounding waters are important for current scientific study. Based on the knowledge we now have, this importance is almost certain to increase in the next couple of decades.

THE IMPORTANCE OF SCIENTIFIC KNOWLEDGE OF THE ARCTIC ISLANDS

Forces Driving Research

To whom is scientific knowledge of the Arctic islands and waters important? To most scientists, to historians, and to those concerned with our natural heritage for its own sake, this question does not have much meaning. Of course the knowledge is important, if it is valuable and available to all. We are fortunate in having a National Museum of Natural Sciences and a Canadian Museum of Civilization that can continue research programs, even though modest and often carried out with insufficient funds, whose principal objectives are to increase knowledge of our arctic heritage. But, whether we desire it or not, most science in the world today - and certainly in Canada - is undertaken to fill a more closely defined policy-mission or practical objective. If we wish to look at the future of research in the Arctic Islands, we should consider the main driving forces for research support in northern Canada generally, and consider how these apply to the archipelago.

The main driving forces are easy enough to identify. All one has to do is to review present expenditures for arctic research, note who is spending the money and why; and to review the arguments put forward by the scientists themselves, or their bosses, as to why they should be funded to carry on research in which they are particularly interested. Many research studies contribute to more than one need or objective; but outside the studies funded by the National Museums and a few private institutions, the main "driving forces" for research in the Arctic Islands today and in the years ahead appear to be as follows:

Defence and Sovereignty

If Canada is the ham in the U.S./U.S.S.R. superpower sandwich, the Arctic Islands is the mustard on top of the ham. All defence-related arctic surveillance and monitoring systems, in the atmosphere and in the waters beneath the ice, require an increasingly sophisticated knowledge of the archipelago. And, from a purely Canadian viewpoint, we are well aware that the deep-draught North-West Passage (a key element in our sovereignty concerns) runs right through the middle of the Arctic Islands. These various issues translate to a higher priority for research in fields of ionospheric geophysics, aeronomy and magnetism,

physical and biological oceanography, hydrography, sea-ice studies, meteorology and climatic studies, as well as high-latitude communications.

Environmental Protection

High on the list of Canadian priorities for undertaking arctic research, in terms of the funding that comes from a variety of sources, is protection of the natural environment. The Arctic Islands play a prominent part in northern environmental studies, both because land and sea environmental characteristics of the archipelago are sensitive to disturbance from a number of causes (so better understanding of environmental processes is needed if effective protection measures are to be applied), and because study and monitoring of the extreme environment of this area can be useful and important to environmental protection and control over a large part of the northern hemisphere. Subjects most important for these studies are: climatology; geomorphology; terrestrial, aquatic and marine biology; environmental biogeochemistry and toxicology; and various pollution-control and cleanup technologies.

Development of Resources

A great deal of the increase of research in the Arctic Islands in the past 25 years has been connected with, or spurred by, the indications of deposits of non-renewable resources and the expectation that, with sufficient knowledge and adequate technology, those resources could be exploited at a profit. The work has achieved a measure of success - two base-metal mines and a small oilfield are now producing in the Arctic Islands. But the drop in prices for both metals and petroleum on world markets, combined with high interest rates and steadily rising costs for arctic industrial operations, have sharply reduced earlier optimistic hopes that the region could become a major generator of local or national wealth in the near future. Along with this more sober picture has come a change in research priorities: attention to a variety of renewable and non-renewable resources and their management; smaller-scale balanced development and the attendant lower-cost technologies; the "geographical service functions" of transportation, communications, and tourism; and greater attention to the historical and natural heritage, as well as local concerns (Hobson, this volume). Many of these changes, and the new areas of basic, applied and management research needed to realize them, are already being reflected in the papers presented in this publication.

Social and Political Development of Northern Regions

In many parts of Arctic Canada, one of the principal causes of change in the character and subject of research has been the political evolution of the northern territories, and the changed needs, awareness and decision-making power of northern peoples themselves. Studies in social sciences and applied fields undertaken according to the priorities of northern residents are still relatively rare anywhere in the North but are increasing, and can be expected to increase still more in the near future. The Arctic Islands have been part of this change, and indeed have been the locale of much research undertaken for and by the Inuit in connection with the discussions on creation of the territory of Nunavut. Such studies include resources inventories; health sciences; community planning and management; research into educational methods; history and archaeology. George Hobson (this volume) has given us a spirited account of the need for future arctic research to be managed to a greater extent by northerners themselves.

One element of the researches undertaken in connection with northern socioeconomic development is the degree to which the studies have an international or circumpolar character, and yet are closely tied to local concerns. All countries around the Arctic Ocean are undergoing political and institutional changes in their northern regions, and the resident northerners are asking for, and in many cases receiving, a greater say in decisions affecting their lives (Christie, this volume). In doing so, they are developing new knowledge. The Canadian Arctic Islands provide a part of that knowledge. The circumpolar northern peoples have developed a communication network to share information and the results of one another's investigations. In this respect they lead the governments of the various arctic nations.

Global Scientific Questions

Some of the most exciting research likely to be carried out in the Arctic Islands in the next couple of decades will be that connected with major international multi-disciplinary research programs. As the northernmost extension of ice-free land in the world, the Canadian Arctic Archipelago is important to many studies of world-wide phenomena. Its unique geophysical, geological, climatic, oceanographic and biological characteristics have meant that the Arctic Islands have played a prominent role in past major world-wide researches, such as the International Polar Year, the International Geophysical Year, the International

Biological Program, the International Magnetospheric Study, and many more. Similarly, these islands figure prominently in the new wave of international world-wide studies now being launched: the International Geosphere-Biosphere Program, the World Climate Research Program, the International Lithosphere Project, the Man and the Biosphere Program, and others. These studies will, if fully developed, bring a wide range of physical, biological and human sciences in the Arctic Islands into close contact with advanced studies in similar subjects in other parts of the world.

NEW TECHNOLOGIES

One of the most striking differences between the researches that can be expected in the next few years in the Arctic Islands and those of the past couple of decades is the difference in research technologies. While the field-scientist traversing on foot or helicopter and making detailed visual observations or simple measurements is not yet a relic of the past, it is increasingly true that in nearly every research subject the advanced research is becoming more instrumented, technological, and quantitative. New technologies not only make possible more precise measurements and investigation of much more sophisticated phenomena than was possible before. They also often offer considerable saving in field costs, and increase scientific productivity per scientist-day in the field compared to older methods. Further, they make it almost mandatory that the leading research, even in the Arctic, be based in a technically-advanced and well-funded institution in lower latitudes. The new research techniques can be expected to find early use in the Arctic Islands, where costs for field work are already the highest in the country.

In many fields, important arctic problems can no longer be adequately studied in the summer or in areas easily reached. To study processes on a year-round basis, in the marginal ice zone, during severe storms or ice break-up requires specialized and often very sophisticated equipment. Thus satellite surveys, various forms of remote-sensing, automatic instrumentation with telemetered observations, sophisticated portable field-laboratories and computers can be expected to become a conspicuous part of Arctic Islands science in the years ahead.

With these changes in technology must come, of course, a change in the type of scientists that work in the Arctic Islands, and in the training that they undergo in the laboratory and in the field. It requires a rather different kind of scientist to sit on a rocky perch for hours recording the mating habits of a polar bear than one who measures the fat-content of the milk of a lactating bear by electrical conductivity, although some scientists can make and, indeed, lead the change. Inevitably, such changes lead to alteration in the way that research projects are formulated and the results evaluated. Research technology not only determines the way in which we seek new knowledge; more than we often realize, the technology determines what knowledge we seek - and find.

For those of us who started research in the Arctic Islands in the dog-team era, things are becoming quite different. It is easier in the field today; no sense in pretending otherwise. And in many ways it is harder - harder to be sure that one is really adding significantly to new knowledge. But the interests, satisfactions, frustrations and fun are all still there.

TRENDS IN SCIENCE

Recent reviews of research programs and individual studies in the Canadian Arctic have shown clear trends in the orientation and scope of the science being pursued. These seem to be typical of nearly all fields of study.

In the Canadian Arctic Islands, although there are many areas in many subjects where data are inadequate and careful observations are few or absent, the descriptive phase (in which the scientist recorded as accurately as possible what was there) has to a great extent been replaced in both natural and social sciences by studies of processes (natural or induced by humans), or of causes and effects of observed phenomena. The emphasis today is not so much on what is there, but on how things got the way they now are, and what changes are currently taking place. These new emphases in turn are leading to a focusing of research on major scientific problems, such as climate change and the migration of vegetation zones (Edlund, this volume), the flow of chemicals through an ecosystem, or the reasons for changes in animal or human populations. As a result - and this is probably influenced by budgets and institutional factors and technologies, as well as by the needs and opportunities

of the science itself - we are seeing more team research. Different disciplines are joining to work on related aspects of the same problem, and there is a closer integration of arctic studies with studies in the rest of the world.

Although much of the emerging research is international in outlook and criteria, the broader context need not mean that the new research is less relevant to local problems. Indeed, international connections in arctic research can serve to bring the knowledge of world science to bear on the distinctive problems of the Arctic Archipelago or its people, as well as to make a contribution from the Canadian Arctic to important problems being studied in other parts of the world.

SOME PROBLEMS

Problems can be foreseen regarding research in general in the Arctic Islands, to which serious attention should be given in the years ahead. Likely, future research in the archipelago will be *even more closely linked to policy priorities* than at present, and this may increase the difficulties of maintaining a balanced advance of knowledge across a wide range of subjects important to an understanding of the region. As a recent study (Adams *et al.* 1987) has shown, Canada urgently needs: (1) *a means to ensure continuing attention and resources for arctic science*; (2) a means for developing *research programs reflecting the priorities of the North* as well as southern Canada; and (3) an effective *polar science information-system*. These needs apply to the Arctic Islands as well as other parts of northern Canada.

Special care may be needed to *integrate or reconcile local priorities for new knowledge with the broader research requirements of international programs*. The high cost and technical sophistication of modern arctic research pose special challenges to the *full participation of northern residents* in planning and conducting research in their own hinterland, and to providing Arctic Islands *research experience to significant numbers of students*.

It is important that these challenges be met, and that the Canadian Arctic Islands yield in future not only knowledge that is of vital national and international importance, but that the islands play a leading role in the practice and the relevance of Canadian science.

If the challenge can be met, then rather than being Canada's missing dimension, the Arctic Islands will add an extra dimension to Canadian science.

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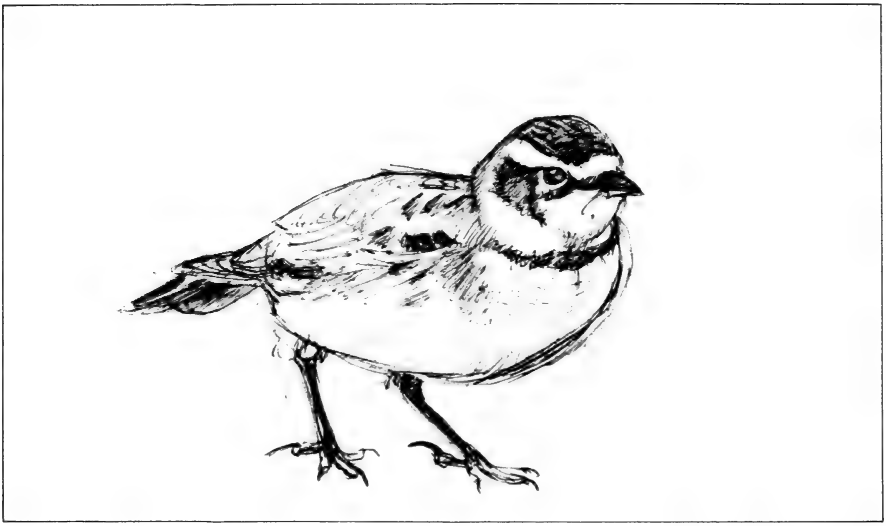
Illustrated by Brenda Carter



Illustrated by Brenda Carter

THE EARTH: FOSSILS AND PALEOENVIRONMENTS

Illustrated by Brenda Carter

PALEOZOIC FISHING - THE FRANKLINIAN GROUNDS

D.L. Dineley[1]

Abstract: The Silurian and Devonian rocks of the Arctic Lowlands around Barrow Strait include formations mostly of shallow marine and continental origins. From a large number of Late Silurian and Early Devonian horizons many agnathan and a small number of gnathostome fishes are known. All the major heterostracan families occur, as do a few cephalaspid species. The anaspids occur early in the sequence but are rare: thelodonts have been found at levels ranging from Early Silurian to Early Devonian in both marine and continental facies. Acanthodian fishes range from mid-Silurian to the top of the local Lower Devonian, and arthrodires occur in the highest levels. The most advanced fishes were the "porolepid" osteichthyans - relatively large forms.

The agnathan cyathaspids, traquairaspids and pteraspids appear to be especially well represented both in numbers of species and individuals. The small protopteraspids are held to originate from small cyathaspids, and subsequent pteraspid evolution was rapid. All of these agnathans are biostratigraphically valuable.

These vertebrate faunas have much in common with their early Devonian contemporaries in Spitsbergen and northwestern Europe, as well as with other regions of North America. This Euramerican province is distinct from those of Siberia, China and Australia.

Résumé: Les roches siluriens et dévoniens des basses terres de l'Arctique autour du détroit de Barrow comprennent des formations qui sont principalement d'origine continentale et marine peu profonde. De nombreux poissons agnathes et quelques gnathostomes ont été identifiés dans un grand nombre d'horizons du Silurien supérieur et du Dévonien inférieur. Toutes les familles principales des hétérostracés s'y retrouvent, tout comme quelques espèces céphalaspides. Les anaspides sont présents au début de l'ère, mais ils sont rares: dans les faciès marins et continentaux, on a trouvé des thélodontes à des niveaux variant du Silurien inférieur au Dévonien inférieur. Les poissons acanthodiens se retrouvent à partir du Silurien moyen jusqu'à la fin du Dévonien inférieur local, tandis que les arthrodires sont dans les niveaux supérieurs. Les poissons les plus évolués étaient les ostéichtyens "porolépides", des formes relativement grosses.

Les cyathaspides agnathes, les traquairaspides et les ptéraspides semblent être particulièrement bien représentés en nombre d'espèces et de spécimens. On considère que les petits cyathaspides dérivent des petits protoptéraspides, et que l'évolution subséquente des ptéraspides fut rapide. Tous ces agnathes ont une importance biostratigraphique.

Ces faunes de vertébrés ont beaucoup en commun avec leurs contemporaines du Dévonien inférieur au Spitsberg et dans le nord-ouest de l'Europe, de même que dans d'autres régions de l'Amérique du Nord. Cette province euroaméricaine est distincte de celles de Sibérie, de Chine et d'Australie.

INTRODUCTION

Since the late 1950s, an increasing number of primitive fossil vertebrates has become known from the Palaeozoic formations of the Canadian Arctic Lowlands (Figure 1). Locally they occur abundantly and represent assemblages of the jawless fishes with minor numbers of other extinct species, including the earliest gnathostomes. The enclosing sedimentary rocks range from early and mid-Palaeozoic marine carbonates to Devonian carbonates and continental red-bed clastics. For over 100 years mid-Palaeozoic vertebrates have been known in Europe and in North America, puzzling the palaeontologists of the day and being variously ascribed to different taxonomic groups. The Canadian materials provide some excellent insights into the anatomies of these ancient and extinct animals and into the

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environments in which the creatures lived. It is also clear that, in company with similar contemporary forms in Europe and Spitsbergen, they were members of a distinct early Devonian biological province some 375-390 million years ago. Contemporary provinces in other parts of the Devonian world, namely Siberia (Angara), China, and Australia-Antarctica (East Gondwana) were inhabited by other early, and presumably primitive, aquatic vertebrate groups. These separate provinces lasted for about 15 million years, by which time most of the agnathous forms achieved a wide geographical range and widespread success before abruptly declining. The fossils from the Silurian and Devonian formations of the District of Franklin, Arctic Canada, illustrate both the rapid and successful development into new local environments and the rapid evolution of several anatomical variations. The picture becomes clearer and more intriguing when the geography of those distant times is taken into account.

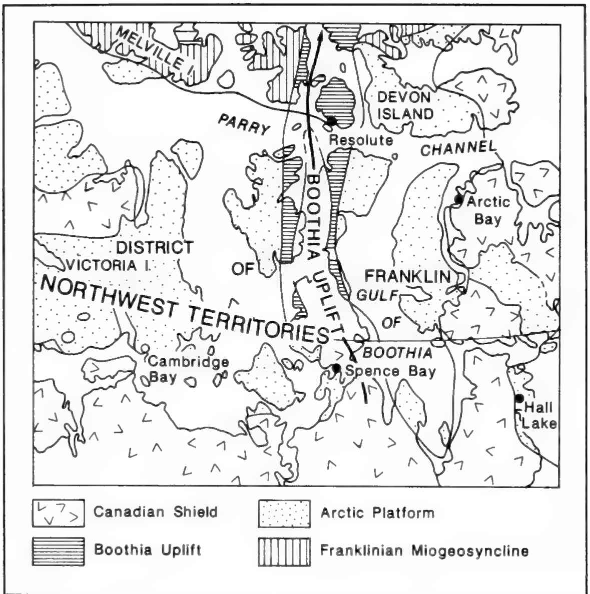


FIGURE 1: The geological setting of the Canadian Arctic Lowlands (after Thorsteinsson and Tozer 1970, p. 550, Figure x-1). The Franklinian miogeosyncline was the deeper water basin lying to the north of the mid-Paleozoic platformal sea. It received predominantly fine clastic sediments, in contrast to the carbonate shelf deposits of the Canadian Arctic Lowlands platform. The Boothia Uplift rose in Late Silurian time to shed its early Palaeozoic cover as a clastic apron onto the platform round about.

The earliest known of all undoubted vertebrates occur in marine formations of Ordovician age, some 125 million years older than those of the early Devonian. Despite the long time-span between these two ages, apparently the vertebrates advanced little in their diversity or complexity. They were shallow-water marine animals throughout that time, well-adapted to modes of life in stable environments, and may have been widely distributed as relatively small populations. The rapid and very important biological changes and events that occurred toward the end of the Silurian period and in the early Devonian profoundly

influenced vertebrate evolution (Chaloner and Lawson 1985), and the evidence of this is present in Canada's North as strongly as elsewhere.

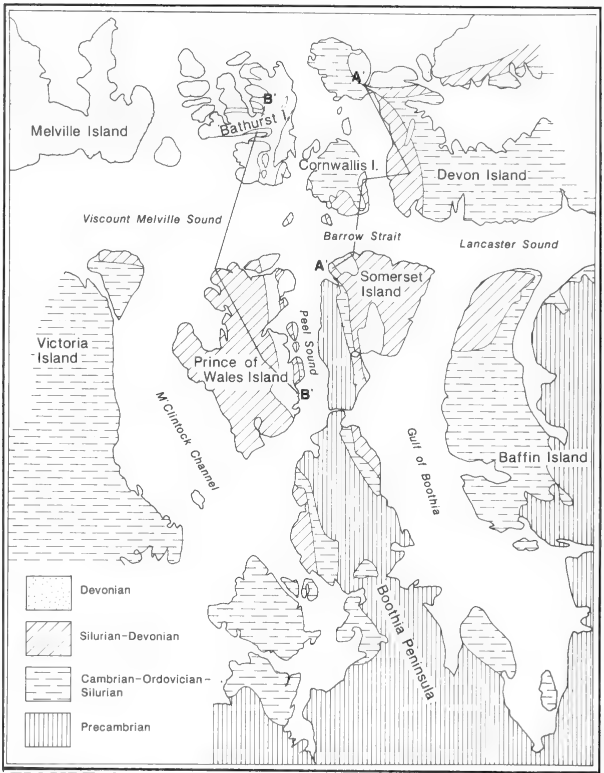


FIGURE 2: The general geology of the area around the Boothia Uplift and Parry Channel (Barrow Strait). The principal vertebrate-bearing formations lie within the Silurian-Devonian and Devonian subdivisions. The sections A-A' and B-B' are shown on Figure 3.

Early Silurian vertebrates are uncommon, even in those areas that are most thoroughly investigated. They are, however, known from the Cape Phillips and Snowblind Bay (geosynclinal) basinal succession on Cornwallis Island, and from horizons as low as Llandoverian and Wenlockian. These fossils are fragmentary and poorly preserved, but are in marine successions datable by graptolites. It is clear that they are exotic introductions from shelf areas of deposition elsewhere (Thorsteinsson 1967, 1980).

The relatively sudden appearance of vertebrate "provinces" after so long a period of stasis amongst these forms of life coincides in large measure with the introduction into the stratigraphic column of the "Old Red Sandstone" facies as common rock-types. In the vicinity of Barrow Strait and Peel Sound, the Silurian carbonates are succeeded by early Devonian clastic rocks derived from older formations in the Boothia Uplift (Figures 2,3). The region was part of a major continental area known now as 'Laurussia' or the 'Old Red Sandstone Continent' (Figure 10). Early vertebrates were first recognized there by Dr.

R. Thorsteinsson and the officers of the Geological Survey of Canada in the 1950s (Thorsteinsson 1967 *et seq.*). Subsequent discoveries were made by Geological Survey of Canada geologists and by expeditions from the University of Ottawa over the next two decades, sponsored in large measure by the National Museum of Canada. An impressive volume of material has been amassed - much of it unique. During the same period remarkable similar discoveries have been made in China, Siberia and the Soviet Arctic.

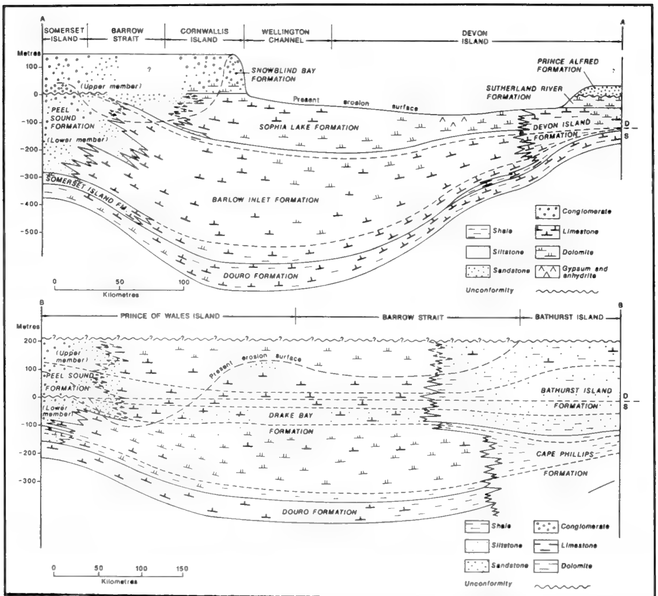


FIGURE 3: Restored stratigraphic sections to show the relationships of Upper Silurian to Lower Devonian rocks in the vicinity of Barrow Strait (after Thorsteinsson 1980). The broken lines represent the approximate positions of formal biostratigraphic boundaries on the basis of local marine faunas. $\frac{D}{S}$ base of the Devonian System. See Figure 2 for map of profiles A-A' and B-B'.

Middle and Late Devonian fishes are present in the successions on Bathurst and other islands northwest of Barrow Strait, but I will confine my comments to the Early Devonian and older formations.

MID-PALAEOZOIC STRATIGRAPHY AND ENVIRONMENTS IN THE BARROW STRAIT REGION

Until Late Silurian (Pridoli) time, much of the region occupied by the islands around Barrow Strait and the Jones-Lancaster Basin was one of shelf-carbonate sedimentation, with deeper water to the north of Cornwallis Island and shallow water and land over the

Canadian Shield (Figure 10). Thereupon the rise of the Boothia Uplift (the Cornwallis Disturbance) produced a finger of land about 800 km long north-south, and 150 km wide. Its core consists of Precambrian crystalline rocks, its flanks are of deformed early Palaeozoic formations within which facies changes occur relative to distance from the Uplift (Brown *et al.* 1969; Kerr 1977; Kerr and De Vries 1976). A summary of the stratigraphy is shown in Figure 3.

The effect of the Cornwallis Disturbance was to create an upland shedding clastic debris to east and west, and bringing about the facies-changes (Figure 3).

These facies-variations may be traced across most of Prince of Wales Island and much of Somerset Island (Broad *et al.* 1968; Miall 1970A; Jones and Dixon 1977) and are known on the islands north of Barrow Strait (Thorsteinsson 1980) in considerable detail. The original broad classification has been much improved (Gibling and Narbonne 1977; Elliott 1983). For example, the Read Bay Formation of earlier accounts is now raised to Group status, its component formations being well identified and of known areal extent. Following are summaries of the principal vertebrate-bearing units now distinguished within the region.

Cape Phillips Formation (Thorsteinsson 1958)

The oldest of the formations yielding vertebrates in this region, it is a thick sequence of Ordovician and Silurian graptolite-bearing argillaceous and carbonate rocks on Bathurst, Cornwallis and Ellesmere islands. It is a lateral equivalent of the Douro and Cape Storm Formations (Figure 3), and it has yielded a few specimens of heterostracan and anaspid fishes (see below for major categories of fishes involved).

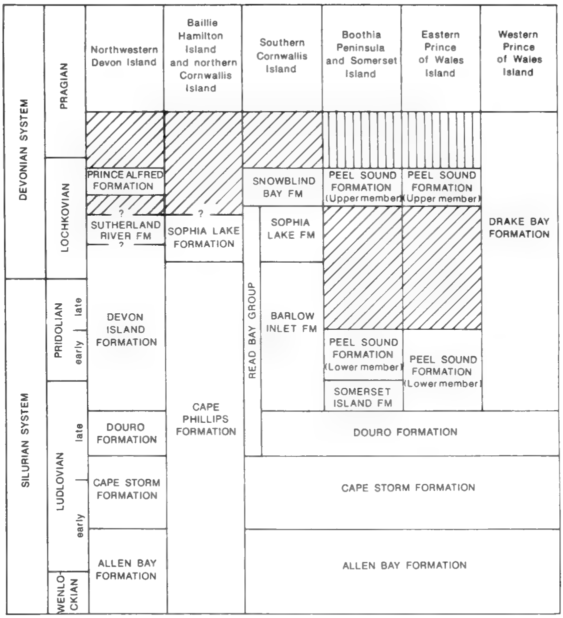
Douro Formation (Thorsteinsson 1963)

This is a thin diachronous late Silurian succession of argillaceous and bioclastic limestones with an abundant shallow-water marine invertebrate fauna. It appears to have been deposited under quiet waters of normal salinity and in two transgressive-regressive cycles. Acanthodian remains occur locally (Narbonne and Dixon 1982).

Cape Storm Formation (Kerr 1975)

This is a very widespread, uniform, homogeneous and thinly-bedded carbonate unit with minor shales. It is as much as 600 m thick on Devon Island but is only 120-260 m thick

TABLE 1: CORRELATION OF STRATIGRAPHIC SUCCESSIONS WITHIN THE BOOTHIA UPLIFT-BARROW STRAIT AREA. OBLIQUE SHADING DENOTES ABSENCE OF STRATA BECAUSE OF UNCONFORMITY IN THE SECTIONS: VERTICAL SHADING INDICATES PRESENT DAY EROSION (AFTER THORSTEINSSON 1980).



on Somerset Island. Fossils within this formation are generally scarce, but locally there are abundant stromatolites and some brachiopods, bryozoa, corals and stromatoporoids. Conodonts and vertebrates are known from several localities in this unit, which is regarded as shallow marine and dominantly subtidal, but in places and at times intertidal and supratidal.

<u>**Somerset Island Formation**</u> (Miall *et al.* 1978)

A unit of mainly grey-pink carbonates with variable minor sand, silt and shale members that is 150-300 m thick on Somerset Island, where vertebrate remains (mostly heterostracan, see below) occur both as scattered fragments and as bone-bed accumulations. Brachiopods, ostracods, arthropods including large eurypterids, corals and stromatoporoids are locally abundant, indicating temporary fully-marine conditions; elsewhere sedimentary evidence is for lagoonal and intertidal environments.

<u>**Leopold Formation**</u> (Jones and Dixon 1975)

A largely dolomitic formation, with stromatolitic limestone and sandy thin-bedded limestones, this unit appears to represent supratidal and high intertidal and lagoonal environments in northeastern Somerset Island. The brachiopod *Lingula* in several beds supports this interpretation. Vertebrates are present as scattered body-plates and isolated scales, probably introduced during storms or other episodes of strong current activity. Possibly this unit is best considered as part of the Cape Storm Formation.

<u>**Peel Sound Formation**</u> (Thorsteinsson and Tozer 1963)

This is a conspicuous red-bed clastic unit formed mainly of detritus derived from the earliest rocks of the Boothia Uplift. Miall (1970A,B) has described the formation in detail and recognized five facies-belts in the upper of the two members seen on Prince of Wales Island. The environments in which the formation accumulated range from fluvial and alluvial fan to marine farther away from the Uplift. On Prince of Wales Island the marine facies have been designated separately as the Drake Bay Formation (Ormiston 1969) and correlative rocks are known on Cornwallis, Devon and Bathurst islands. Vertebrate remains are common at many levels in all but the coarsest facies (Elliott 1984).

Sophia Lake Formation (Thorsteinsson 1980; Muir and Rust 1982)

Consisting of limestones and dolostones with minor siltstone and sandstone, the Sophia Lake Formation is thought to be a shallow-water possibly intertidal unit (Gibling 1978). Acanthodian scales and spines are known.

Barlow Inlet Formation (Thorsteinsson 1980)

Members B and C of the Read Bay Formation on Cornwallis Island described by Thorsteinsson (1958) were later relegated to this unit. They consist principally of shelf-carbonate rocks with many intercalations of shale, sediments deposited in a subtidal regime, perhaps at the far edge of a tongue of detritus spreading out from the rising Boothia Uplift to the south. Fossils are locally abundant marine invertebrates, and disarticulated vertebrate remains are also common in places. Scales and spines of acanthodians and thelodonts occur in profusion, with fragments and plates from large and small heterostracans.

Snowblind Bay Formation (Thorsteinsson and Fortier 1954)

This is a coarse limestone breccia and conglomerate unit of apparently northern and northwestern derivation, rather than from the Boothia Uplift. Vertebrates occur in the lower part of the formation.

THE FOSSIL VERTEBRATES

The preservation of skeletal materials depends not only on the death-environment of the animal, but also on many factors operating before burial in sediment takes place. Currents, waves and storms, not to mention the agencies of biological decay and the activities of scavengers, are all especially important where the animal is aquatic. The vertebrates mentioned here had little hard internal skeleton, but possessed extensive bony "armour" or exoskeletal protection, as well as thick bony scales and spines.

The modes of occurrence of these vertebrate fossils range from isolated scales and fragments a few millimetres in size, and in barren coarse clastic matrices, to dense concentrations of fragments and entire head or body armour in finer clastic sediment. Articulated specimens are rare but several instances of relatively complete fossils are known.

(Dineley 1968, 1976). In the carbonate facies, "bone-bed" accumulations of vertebrate debris are common on northern Prince of Wales Island, whereas isolated but numerous well-preserved exoskeletal plates occur in many areas. R. Thorsteinsson (personal communication) has discovered several instances of remarkably complete pteraspid and other carapaces or squamation in the carbonate-facies of this region. Probably the vertebrates were variously distributed between the freshwater, brackish and marine environments. Sudden inundations may have swept non-marine forms from their habitats into the sea, but it also appears that many fish (agnathans, thelodonts and acanthodians) were capable of a marine existence or may have migrated seasonally between sea and fresh water. The numbers of different vertebrate species present at a locality ranges from one to as many as 15; most localities seem to yield about five species, and these are commonly of heterostraci. Additionally there may be one or two species of cephalaspids, plus acanthodian and thelodont scales or spines that are difficult to identify closely.

The marine environments supported a rich benthonic invertebrate fauna, part of a complex ecosystem that may have been highly productive and capable of supporting a variety of vertebrates. The continental environments undoubtedly supported algal and primitive vascular floras with perhaps attendant invertebrates. Some of these environments, especially the lacustrine, may also have been "vertebrate-friendly" habitats. A discussion of the nature of the radiation and dispersal of the agnatha in Late Silurian-Early Devonian times is given elsewhere (Dineley, in press).

Most of the fossils belong within three broad categories, ostracoderms, placoderms, and gnathostomes.

Ostracoderms were jawless forms with extensive exoskeleton about the head and body, and with thick bony scales on the hind parts (Figure 4). Some were dorso-ventrally flattened, others were fusiform (spindle-shaped). In size they range from 3-5 cms to 30 cms or more long. They are probably related to modern lampreys and hagfishes. The Heterostraci were ostracoderms with a head and body armour of several paired plates set around central dorsal and ventral discs (Figure 5). Paired fins are unknown but the tail was stout and used for propulsion. The Osteostraci were ostracoderms possessing a solid cranial skeleton, flattened, and horseshoe-shaped in plan and with ventral mouth and gill-openings and a scaled, laterally compressed body and tail. Most forms had small pectoral fins.

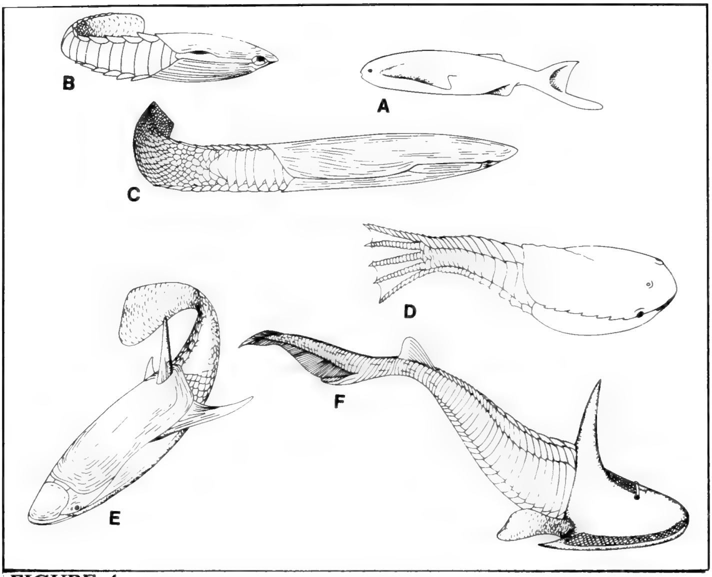


FIGURE 4: Various types of mid-Palaeozoic agnatha (ostracoderms). These forms are among the few that are known from relatively complete skeletons. A. Thelodus, a small form lacking bony plates (length 3-8 cm); B. Anglaspis, with several large plates covering the forepart of the body, and with large bony scales behind (about 8 cm long); C. Torpedaspis, a long narrow agnathan, common in the Peel Sound Formation on Somerset Island (up to 35 cm long); D. Ctenaspis, a short deep-bodied form with a large tail-fin (about 10 cm long); E. A pteraspid, a common form with many genera, some individuals of which reached 30 cm long; F. Machairaspis, a cehalaspid known in Spitsbergen and Arctic Canada (about 30 cm long).

Anaspids were jawless, entirely covered with small lozenge-shaped scales; in place of the normal paired-fins were two long lateral-fins on the lower body. They are known in the Cape Phillips Formation of Cornwallis Island, but await description (Thorsteinsson 1967).

Thelodonts were dorso-ventrally flattened fishes about 5-10 cm long with terminal mouths and a body-covering of tiny stud-like scales. The oldest thelodonts occur in Llandoverian-age rocks on Cornwallis Island, whereas the youngest are from the Peel Sound Formation (Turner and Dixon 1971).

The cephalaspids (Osteostraci) are known from relatively few well-preserved fossils, mostly headshields. The head and gill parts were encased in a solid box of bone, which was dorso-ventrally flattened and somewhat horseshoe-shaped in plan. Behind it the body was rather laterally compressed, triangular in cross-section and covered in longitudinal rows of small elongate scales. The upper surface of the head shows two close-set eyes near the

median line with a simple nasal opening and a tiny pineal opening between them. The most conspicuous feature of this surface is the presence of two lateral "fields" and a dorsal "field" covered in tiny bony plates. They are connected to the vestibular part of the ear by several large canals, and seem to have had some form of sensory function. On the flat undersurface of the head is a jawless mouth with pairs of gill-openings at the margin of a subcircular central scale-area. Apparently there were deep paired gills within the head, and water was kept moving through the mouth and gills by a flexible floor - perhaps pulsing up and down. The whole internal anatomy of the head is very like that of the modern hagfish (*Petromyzon*).

Most Canadian cephalaspids were about 15 cm long, but an early form (*Hemicyclaspis*) from Somerset Island was about twice that length. Like many other genera, it had a pair of scaled 'flippers' behind the cornual (lateral) angles of the head shield. Cephalaspids were probably benthonic, but reasonably active swimmers on occasion. The strong tail fin suggests as much.

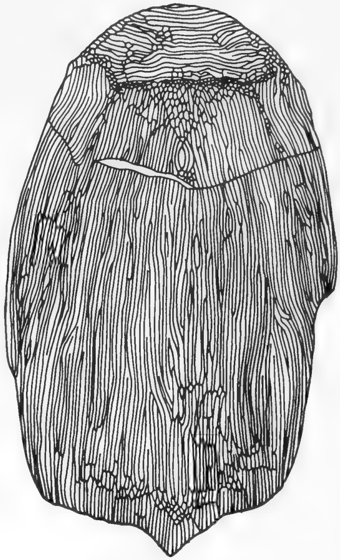


FIGURE 5: Top: The dorsal shield of a typical small cyathaspid (**Archegonaspis**) from the Late Silurian of Somerset Island shows a relatively simple pattern of lines developed on the smooth external surface of the bone. Many cyathaspids have patterns of lines that are diagnostic of the species (after Loeffler and Jones 1976). Bottom: Thelodont denticles; **Logania**, a genus of Late Silurian thelodonts from eastern Prince of Wales Island (after Turner and Dixon 1971). The length of each denticle is between 0.3 mm and 0.5 mm. The animal possessed several thousand such denticles in its skin, the shape of denticle varying with position on the body (Figure 4).

Rather like the cephalaspids, were the anaspids, which are rare but have been discovered in the Canadian Arctic Islands by R. Thorsteinsson. Anaspids are much the same size as the cephalaspids, but covered in small bony platelets and scales. They were fusiform and rather laterally-compressed fishes having jawless terminal mouths, small eyes and a row

of gill-openings on each side of the head. They seem to have lacked lateral fins but had a strong hypocercal tail. Anaspids were probably active swimmers that have been variously regarded as surface film-feeders or as suctionally grazing the bottom sediment.

The great heterostracan group, the pteraspidomorphs, are very diverse and most abundantly represented in the Arctic Islands. They had a set of well-defined bony plates covering the head and thorax; the hind part of the body and the tail were covered by sets of bony scales, all minutely and distinctly ornamented. Many new forms are known (Elliott 1983, 1984). From the relative simplicity of their armour, the cyathaspids are regarded as the 'basic heterostracans', and they appear earliest in the fossil record.

The cyathaspid head had a few paired plates around central dorsal and ventral median plates, and the body was clad in thick scales. There were no lateral fins. The mouth was at or near the front margin of the head, and the small eyes were on the front lateral margin. Water taken in through the jawless mouth passed through paired gill-chambers and left through openings near the rear of the carapace. The opening of the mouth could be expanded by lowering the array of small oral plates on its lower side. While some species had rather flat underbellies and rested on the bottom, some seem to have lain with flat dorsal sides at the sediment-water interface; others had the torpedo-like bodies of fish that lived amongst fronds of water weed. The more architecturally-complex pteraspids possessed a median dorsal spine, or vane, and cornual spines or planes, which must have been hydrodynamically important. However, the mode of life and activities of these animals remain largely conjectural. The earliest pteraspids seem to have evolved from an advanced group of small cyathaspids, but soon evolved species larger and more varied in shape. They occur in both marine and non-marine sediments (Elliott 1984).

Somewhat earlier to appear in the succession of cyathaspid-like agnatha were the traquairaspids. This group had a most characteristic tubercle-like surface ornamentation on its plates and scales, and in some species there was a smooth central area on the ventral median disc. Some palaeontologists believe that the tubercle ornamentation is a primitive character persisting from earlier forms, each turbercle representing an ancestral scale.

Broad (1973) described three species of the new genus *Boothiaspis* from several horizons in the Canadian Arctic Islands. He believed them to be members of a separate Order, Amphiaspidiformes, previously only known from the northwestern Siberian Platform and southwestern Taimyr (Novitskaya 1971). They have flat dorsal shields, as much as

20 cm in length. The material is, so far, still meagre, and the true affinities of these fossils are not established beyond doubt. Elliott and Dineley (1985) believe that they are cyathaspids.

The Thelodonti, a very poorly known group of small agnathans, have head, trunk and tail regions covered with denticles rather than scales (Figure 6). Complete specimens are extremely rare, but both flattened (skate-like) and rather minnow-shaped body forms are known. In the Canadian biotas the thelodonts are represented by isolated denticles in both marine and non-marine formations.

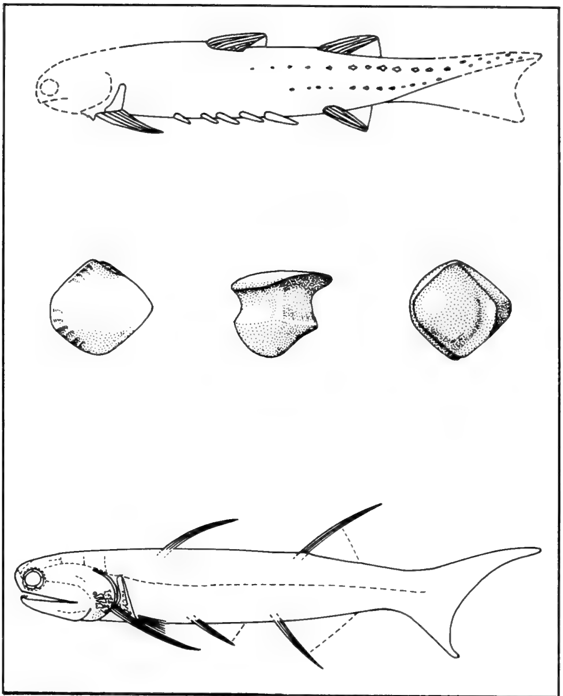


FIGURE 6: Acanthodians are represented by bony spines and dermal denticles (centre). Top: Lupopsyrus, about 4.5 cm long. Bottom: Ischnacanthus, about 10-15 cm long; the denticles range between 0.5 and 1.0 mm in diameter, and formed a dense cover over the entire head and body of the fish.

Representing the major, but rather ill-defined group, the placoderms, are the arthrodires (e.g. *Eskimaspis arctica*, *Baringaspis dineleyi*). They are represented by several species in the Peel Sound Formation. The cranial covering of bony plates articulated with those of the pectoral region, and there were simple but efficient joints. All the exoskeletal plates were clearly ornamented by small almost star-shaped tubercles. From each side of the forward part of the body projected bony cornua or spines, which may have assisted in hydrodynamic stability. Small pectoral fins lay immediately behind these projections. The tail tapered rapidly and was covered by thin scales. Arthrodires are never common in these faunas and were probably predators or scavengers (Miles 1973; Dineley and Liu 1984).

Comparatively rare but widespread among the Canadian early vertebrates are the acanthodians, "spiny sharks" - the first true jawed or gnathostome fishes (Figure 7). They were minnow-like, small and active animals with minute square-crowned scales and stout bone spines at the leading edge of dorsal, anal and paired fins, and with an elegant heterocercal tail fin. Acanthodians had an internal skeleton and various small bones in the complex head assemblage. Conspicuously large eyes were set well forward on the blunt head and above the well-developed jaws. Teeth in some species were numerous, sharp, and arose directly from the jaw cartilage: they also occur as centrally-placed whorls of multicusp teeth held to the jaw cartilage by connective tissue. Apparently these jaws belong to rapacious, or at least carnivorous, little fish that were mid- or surface-water feeders. Articulated fossil acanthodians are rare but are known elsewhere in formations of marine character as well as in those (e.g. the Peel Sound Formation) that are probably fluvial in origin.

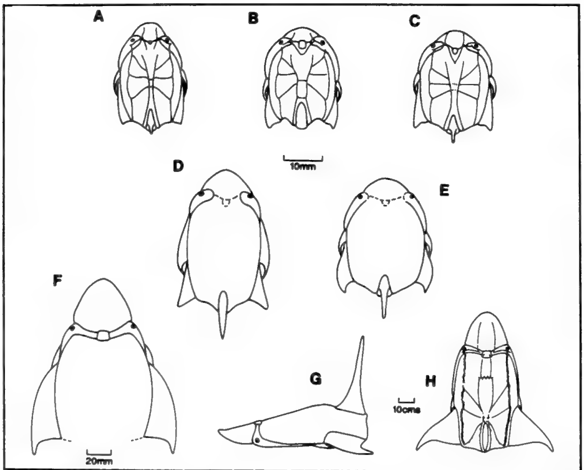


FIGURE 7: Pteraspids show many variations in the architecture of the dorsal shield. A-E are small early forms from the lower member of the Peel Sound Formation: F-H are larger and from the upper member of the same formation. A, B and C show the sensory-canal lines: the orbits that contained the eyes are black. Note size differences indicated by the scale bars A-E, F, and G and H. A. Protopteraspis sartokia, southeastern Prince of Wales Island; B. P. siliktokia, southeastern Prince of Wales Island; C. P. pygmaea, eastern Prince of Wales Island; D. P. (?) arctica, southern Somerset Island; E. P. (?) corniga, northwestern Somerset Island; F. Escharaspis alata, reconstruction of the dorsal shield. Prince of Wales Island, Peel Sound Formation; G. Unarkaspis schultzei, reconstruction of the dorsal shield in side view; H. Reconstruction of the dorsal shield (top view) showing the sensory-canal system. Northern Prince of Wales Island and eastern Cornwallis Island.

Occurring with pteraspid and arthrodire remains in the calcareous facies of the Peel Sound Formation is at least one species of large gnathostome fish. It is a member of the porolepid group, probably a large active predator (Bernacsek 1975). The head-covering of bony plates and the scales have innumerable tiny holes or pores in the outer shiny surface - hence the name. A similar if not identical fossil gnathostome, *Powichthys thorsteinssoni*, has been described from the Drake Bay Formation on the west coast of Prince of Wales Island by Jessen (1973). Stout and well-armed with sharp teeth, such fishes were perhaps

to be found lurking at the edge of schools of agnatha, or lying in wait for prey amidst weeds of lagoons and watercourses. These are some of the earliest true jawed-fishes known anywhere, though a few fossils of a comparable type have been found in rocks of this relatively early date in Spitsbergen, Europe and China. In later Devonian times they grew to a metre or more in length.

The paleoecology of these vertebrates is poorly understood. There is much scope for work on the swimming and hydrodynamics of the animals, as the head and body shape are well known and some tails have been discovered intact. Feeding habits and general behavioural studies are more difficult to conjecture, but most forms of the Heterostraci seem to have been members of small schools rather than solitary, to judge from the numbers present at certain levels. Some trace fossils (burrows and trails) are known in the sandy strata: invertebrate body fossils occur rarely but giant eurypterids are known. Synecological principles can rarely be suggested as most of the vertebrate assemblages are thanatocoenoses

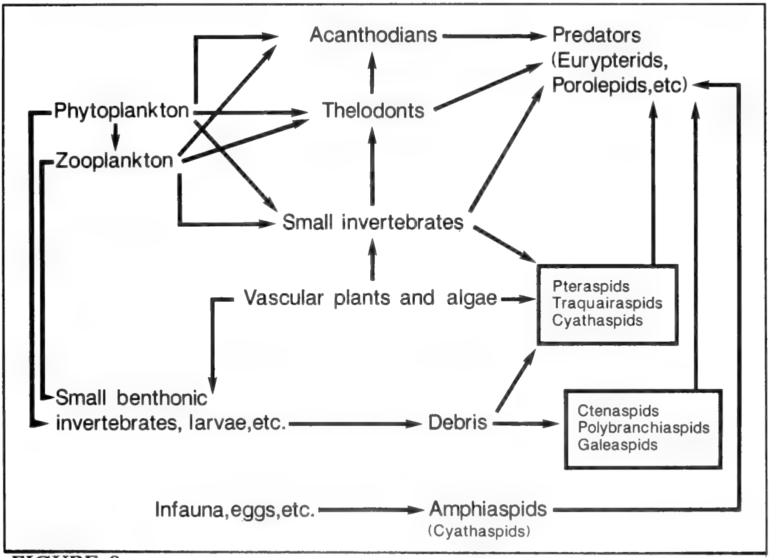


FIGURE 8: A possible general ecological model for early vertebrates, based on agnatha from all of the vertebrate provinces. The amphiaspids seem to be exclusively Siberian, the polybranchiaspids and galeaspids Chinese. The amphiaspids, being blind may have been burrowers. The ctenaspids (and polybranchiaspids and galeaspids in China) may have been active at the bottom sediment-water interface, where conditions tended toward the anoxic. Pteraspids, traquairaspids and most cyathaspids were benthonic or nektonic in habit. Porolepids and other gnathostomes were active nekton as were the thelodonts.

("death assemblages"). I have tentatively suggested an ecosystem model (Dineley 1984) (Figure 8).

The use of early vertebrates in the biostratigraphy of mid-Palaeozoic rocks has advanced recently (Dineley 1984), especially in northern Canada (Thorsteinsson 1980; Elliott 1984). Correlations between this area, Spitsbergen and Europe rest upon a significant number of generic and specific similarities in the vertebrate fauna. There is no doubt that the faunas from these localities all belong to a single palaeobiological province.

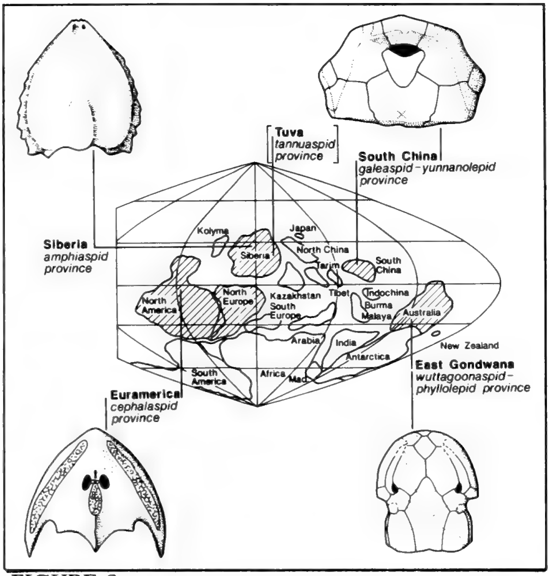


FIGURE 9: Early Devonian Biogeographic Provinces as distinguished by Young (1981). Illustrated are dorsal views of an amphiaspid and a cephalaspid headshield, the cranial plates of a yunnanolepid antiarch and of a wuttagoonaspid arthrodire. In this reconstruction of world geography Arctic Canada lies somewhat south of the Equator (cf. Figure 10).

EARLY DEVONIAN VERTEBRATE BIOGEOGRAPHY

Young (1981, 1986) has suggested that five biogeographical vertebrate provinces may be distinguished from faunal lists of the Early Devonian: Euramerica, Siberia, Tuva, South China and Eastern Gondwana (Figure 9). The northern four were separated from that of Gondwanaland by a persistent marine barrier. Each northern province is characterized by a distinctive assemblage of Agnatha, whereas the East Gondwana province is recognized by the presence of wuttagoonaspid placoderms. South China perhaps hosted the most distinctive faunas: its agnathans include bizarre forms and others with possible adaptations to almost anaerobic environments. The Siberian (Angara) endemic fauna included several blind agnathans. Relative isolation of these provinces may have been responsible for this endemism, but it faded in importance by the end of Early Devonian time.

The Euramerican Province, typified by the cephalaspids and the Heterostraci mentioned above, is perhaps both the largest and the most studied province. Its early Devonian vertebrates have long been known from the British Isles, other parts of western Europe and Spitsbergen (Blieck 1982). More recently the North American faunas have been investigated, notably by Denison (1963, 1964) and by a group associated with the Universities of Ottawa and Bristol (Dineley 1968, 1976; Elliott 1983, 1984A,B; Loeffler and Jones 1976; Loeffler 1977). Dineley (1967) was able to establish very detailed biostratigraphic vertebrate correlation between Nova Scotia and the British Isles. Elliott (1984A) has been able to demonstrate the correlation of Canadian Arctic Islands early Devonian vertebrates with the successions in Spitsbergen, Podolia (U.S.S.R.) and Britain. The wealth of taxa upon which these correlations are made is shown in Table 2.

Apparently conditions favourable to early vertebrates prevailed throughout almost the entire coastal-waters zone of the (Euramerican Province) Old Red Sandstone Continent. As time progressed these fishes penetrated more and more the inland freshwater systems. Middle Devonian time saw the establishment of considerable lake-systems with abundant fishes, but none are known definitely at an earlier date. Tropical humid climate allowed the extensive development of inland drainage-systems and the growth of an extensive plant basis for vertebrate-topped ecological pyramids.

THE SIGNIFICANCE OF THE CANADIAN ARCTIC MATERIAL

The availability of many new fossils offers data to improve our understanding of the anatomy and functional morphology of poorly-known and extinct groups of primitive vertebrates. Their evolutionary relationships, the structure and habitats of their communities and possible ecological relationships are becoming clearer. Our improved knowledge of their biogeographical and stratigraphical ranges is important in understanding Devonian correlation and the Devonian biosphere. The Canadian Arctic materials can be compared with those from elsewhere around the Old Red Sandstone Continent. Species in common with those of Yukon and of Spitsbergen are now recognized, and the geographical range of individual species along this portion of the continent's edge may soon be known.

TABLE 2: VERTEBRATE ?COMMUNITIES FROM FORMATIONS ON SOMERSET ISLAND MAY INCLUDE THE FORMS IDENTIFIED HERE. THEY ARE BROADLY USEFUL IN CORRELATION WITHIN THE REGION, AND EVEN WITHIN THE ENTIRE EURAMERICAN PROVINCE. AS MOST OF THESE FOSSILS ARE IN TRANSPORTED "DEATH ASSEMBLAGES", IT IS UNCERTAIN THAT THEY REPRESENT NATURAL LIVING ASSOCIATIONS. THE PROCESS OF FOSSILIZATION MAY HAVE BEEN SELECTIVE: ONLY THE MORE HEAVILY SKELETONIZED FORMS MAY BE REPRESENTED. THE DASHED LINES REPRESENT THICKNESSES OF BARREN STRATA BETWEEN THE FOSSILIFEROUS BEDS (BASED ON ELLIOTT 1984).

PRESSURE POINT

Peel Sound Formation	*Rhachiaspis pteriga* *Torpedaspis elongata* *Pionaspis sp.* *Corvaspis sp.* *? Traquairaspis sp.*	
	– – – – – – – – – – – –	
Somerset Island Fm. U. Member	*Torpedaspis elongata* *Pionaspis sp.* *Corvaspis sp.* *? Traquairaspis sp.* *Cephalaspis sp.* Acanthodii *indet.*	
	– – – – – – – – – – – –	
	Ulutitaspis aquilonia *Boothiaspis alata* *Torpedaspis elongata* *Corvaspis arctica* *Hemicyclaspis murchisoni* *? Traquairaspis sp.* Acanthodii *indet.*	
	– – – – – – – – – – – –	– – – – – – – – – – – –
Somerset Island Fm. L. Member	*Ulutitaspis notidana* *Rhachiaspis pteriga* *Boothiaspis alata* *Torpedaspis elongata* *Pionaspis acuticosta* *?Traquairaspis sp.* Ancanthodii *indet.*	*Boothiaspis ovata* *Torpedaspis elongata* *Pionaspis sp.* *? Traquairaspis sp.* Acanthodii *indet.*
		– – – – – – – – – – – –
		Ariaspis ornata *Pionaspis sp.*

WEST CRESWELL

Somerset Island Fm. U. Member	*Rhachiaspis pteriga* *Corvaspis sp.* *? Traquairaspis sp.* *Protopteraspis corniga* *Protopteraspis sp.* *Corvaspis sp.* *Pionaspis sp.* *? Traquairaspis sp.*
	— — — — — — — — — — — —
	Boothiaspis ovata *Torpedaspis elongata* *Pionaspis sp.* *Corvaspis sp.* *? Traquairaspis sp.*

CAPE ANNE - CUNNINGHAM INLET

Somerset Island Fm. U. Member	*Anchipteraspis crenulata* *Torpedaspis elongata* *Pionaspis sp.* *Corvaspis sp.* *? Traquairaspis sp.* Acanthodii *indet.*

So far, several reconstructions of the entire animals have been attempted (Broad and Dineley 1973; Dineley 1968, 1976) and the modes of life of particular forms as largely infaunal or semi-buried have been suggested.

Ecological studies have yet to be made, but data relevant to some localities are now sufficient for them to begin.

Evolutionary relationships have been most successfully postulated in the case of the early pteraspids. Elliott's work (1984A) has shown that the group may be derived from cyathaspid ancestors in earliest Devonian time. However, the origins of the traquairaspids, a group abundantly represented in both Somerset Island and Peel Sound formations, remain obscure. The cyathaspids themselves have been regarded as the simplest group of the heterostracans, originating well before Late Silurian time. Many very small cyathaspid fossils found on Somerset Island at low stratigraphic levels await study. It is clear that the cyathaspids are a more varied group than previously suggested and that fundamental taxonomic revision of the cyathaspids is necessary.

In biogeographical terms the Arctic discoveries confirm the distinctive character of the Euramerican (Cephalaspid) Province. The possible connection with the Angara (Amphiaspid) Province provided by the identification of *Boothiaspis* as an ?amphiaspid has not been supported by further discoveries (Elliott and Dineley 1985). Oceanic deep waters may have been a barrier to the migration of the agnatha from one continent to another at the beginning of the Devonian period. Connections between the Franklinian Arctic Canadian terrain and more distant parts of the Laurussian continent (Western Europe and the U.S.A.) are well established on the basis of faunal lists. Nevertheless, there are striking differences between the faunas of the different areas. For example, there are over 25 different osteostracans known from Spitsbergen, whereas only about five different forms are so far determined from the Canadian Arctic. The Canadian localities yield many species of traquairaspids (not all described), while only three or four are known in Europe. The genus *Protopteraspis* is widespread but its forebears appear to be limited, so far, to the vicinity of Prince of Wales Island. The most complex fauna yet known is from Spitsbergen, where one level yields 30 genera, all but seven being agnatha. Probably the acme of diversity is achieved in the late Lochkovian (=Gedinnian) stage of the Lower Devonian throughout the entire Euramerican Province (Figures 10,11). Decline from this point was fairly rapid.

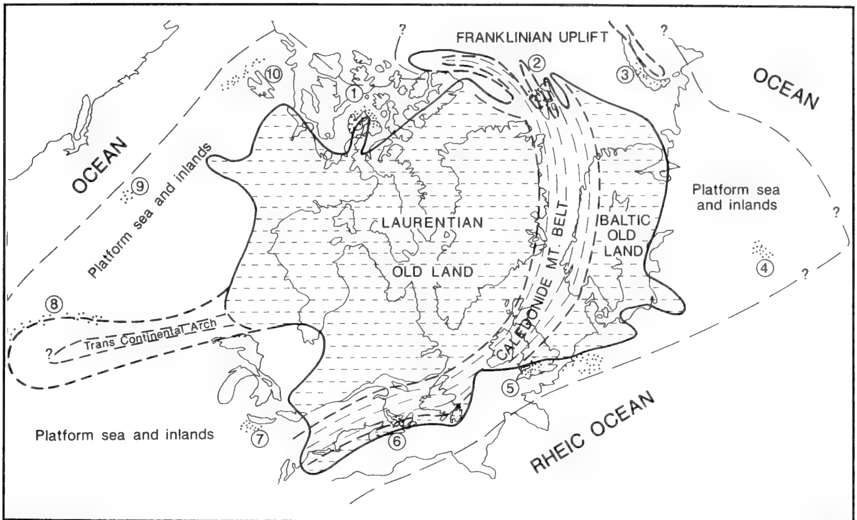


FIGURE 10: **The Euramerican Vertebrate Province: an oversimplified map of the Old Red Sandstone Continent (Laurussia) and its surrounding waters in early Devonian time, showing the principal regions (stippled) in which vertebrates have been found. Key: (1) Canadian Arctic Islands (District of Franklin); (2) Spitsbergen; (3) Novaya Zemlya (U.S.S.R.); (4) Podolia (U.S.S.R.); (5) Western Europe (British Isles - West Germany); (6) Acadia (Maritime Provinces, Canada); (7) Ohio - New York (U.S.A.); (8) Nevada - Wyoming (U.S.A.); (9) Alberta (Canada); (10) Selwyn - Mackenzie Mountains (Northwest Territories, Canada). The full extent and relief of the Trans Continental Arch is uncertain. The equator lay a little to the south of the European margin of the continent and along the bottom left of the map.**

The thelodonts appear to be an exceptional group in that, throughout their history, they were probably capable of a fully marine existence. While they were common in the waters about Laurussia between mid-Silurian and the end of Early Devonian time, they then became extinct there. However, they did survive until Late Devonian time in Australia.

The great majority of ostracoderms died out by the end of the Early Devonian. Nevertheless, in Canada two genera of cephalaspids and two of anaspids are found in the Late Devonian. They occur as 'living fossils' among the Late Devonian gnathostome fishes of the Escuminac Formation in Quebec, where they may have persisted in an intermontane basin refuge. The Franklinian grounds offered no such shelter to local ostracoderms. Halstead (1987) shows that different groups throughout the world died out at slightly different times. What crises brought about the major extinctions, and thereafter the final demise of agnathan groups, remain unknown. Competition from gnathostomes seems to be among the most probably causes.

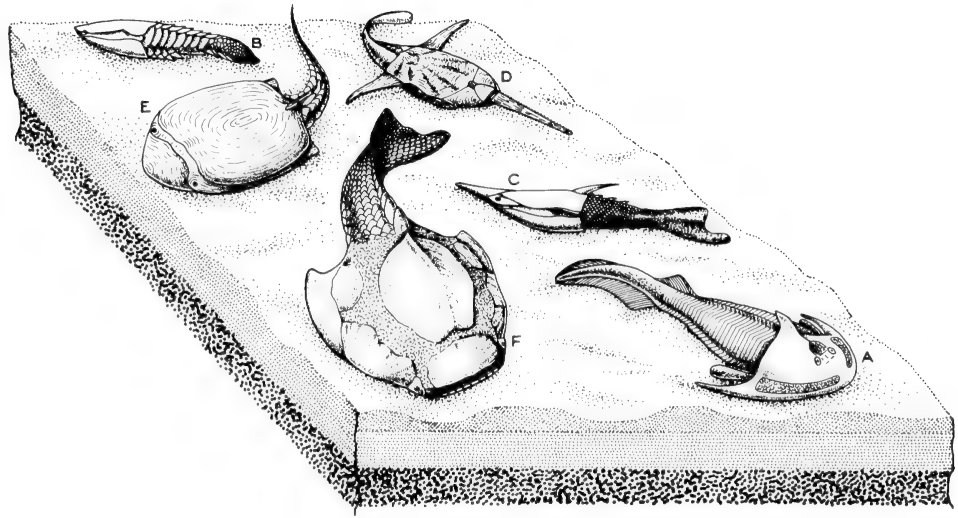


FIGURE 11: Agnathans from various parts of the Euramerica Province (Cephalaspid Province). A. a generalized cephalaspid such as has been found in many parts of the province; B. Anglaspis, a small cyathaspid known in Arctic Canada, Spitsbergen and Europe; C. Pteraspis, a medium-sized pteraspid found in Europe; D. Doryaspis, a bizarre pteraspid known only in Spitsbergen; E. Zascinaspis, a large "blunt-nosed" pteraspid known from Europe (Podolia) and in North America; F. A late psammosteid ostracoderm from Germany found in association with marine invertebrates; in this type of ostracoderm the bony plates were separated from one another by mosaic areas of small platelets. So far no specimens of this kind have yet been found in North America (after Dineley 1984).

ACKNOWLEDGEMENTS

I am indebted to many Canadian colleagues and friends for their kindness and assistance over a very long time. Much of my early work was supported both financially and materially by the Geological Survey of Canada and by the National Museum of Canada. Dr. E.J. Loeffler and Dr. D.K. Elliott, themselves able contributors in this field of study, have generously and helpfully commented on a draft of this paper.

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MESOZOIC VERTEBRATES OF ARCTIC CANADA

Dale A. Russell[1]

Abstract: The oldest remains of Mesozoic vertebrates in Arctic Canada belonged to primitive ichthyosaurs. The single record of a late Triassic terrestrial reptile is based on a trilophosaur vertebra, formerly believed to be dinosaurian. Ichthyosaur and plesiosaur remains are broadly distributed across the Sverdrup Basin in sediments of middle and late Jurassic age, representing taxa closely allied to contemporaneous forms in Europe and midcontinental North America. During late Cretaceous time, marine fishes, reptiles and birds known from the midcontinent frequented the borders of the opening Arctic Ocean Basin in surprising abundance and diversity. Although remains of land-dwelling dinosaurs have recently been discovered in Alaska in close proximity to the paleopole, so far only a single dinosaur (hadrosaur) bone has been found in the Canadian Arctic Islands. This specimen, from Bylot Island, is currently the world's most northerly record of dinosaur bone.

During Mesozoic time both marine and continental vertebrates inhabiting the boreal region were similar to some forms in mid-latitudes, suggesting that both regions were integrated into a single subplanetary ecosystem dominated by seasonal changes in temperature and daylength.

Résumé: Les vestiges les plus anciens de vertébrés du Mésozoïque dans l'Arctique canadien appartiennent aux ichthyosaures primitifs. La seule occurrence de reptile terrestre datant du Triassique supérieur s'appuie sur une vertèbre de trilophosaure, que l'on croyait autrefois provenir d'un dinosaure. Des restes d'ichthyosaure et de plésiosaure sont largement répandus dans le bassin de Sverdrup, dans des sédiments datant du Jurassique moyen et supérieur, représentant des taxons très proches des formes contemporaines rencontrées en Europe et dans le centre de l'Amérique du Nord. Pendant le Crétacé supérieur, des poissons de mer, reptiles et oiseaux appartenant au centre du continent se retrouvaient sur les bords du bassin de l'océan Arctique en diversité et quantité surprenantes. Bien que des restes de dinosaures terrestres aient été récemment découverts en Alaska, tout près du paléo-pôle, un seul os de dinosaure (hadrosaure) qui a été découvert dans les îles de l'Arctique canadien jusqu'à maintenant. Provenant de l'île Bylot, ce spécimen est présentement l'os de dinosaure le plus septentrional du monde.

Durant l'époque du Mésozoïque, les vertébrés des mers et des continents qui habitaient les régions boréales ressemblaient à quelques formes retrouvées aux latitudes moyennes, ce qui laisse penser qu'un vaste écosystème dominé par des changements saisonniers de température et de durée d'éclairement, englobait les deux régions.

INTRODUCTION

To one accustomed to preservation conditions in lower latitudes, Mesozoic sediments in the Canadian Arctic seem rather poorly consolidated, and plant remains appear to be somewhat more abundantly preserved within non-marine strata. Although Mesozoic sediments are exceptionally well-exposed, vertebrate fossils have never been found in abundance within them. All of the fossil vertebrate occurrences in the Queen Elizabeth Islands known to the author are summarized here, as well as those from nearby regions. Supporting references are minimal in number, and the citations they contain should be examined for information on the vertebrate localities. Balkwill *et al.* (1983) provide an excellent regional stratigraphic overview.

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TRIASSIC OCCURRENCES

The first remains of Mesozoic fossil vertebrates to be recovered from the Arctic Islands (and Canada) were collected as a result of the Belcher Search Expedition's efforts to learn the fate of the lost Franklin Expedition. In 1852, on tiny Exmouth Island in Belcher Channel, ichthyosaur vertebrae (Owen 1855; Figure 1) were collected from sediments of middle Triassic age (Anisian-Karnian, Schei Point Formation; Tozer 1961, p. 15, Figure 4; Balkwill 1983; Tozer 1984, p. 41). Vertebrate fossils subsequently collected from this locality by Tozer include *Acrodus* teeth (NMC 9947, identified by W. Langston), a pavement-toothed elasmobranch (shark) also known to occur in Triassic sediments on Spitsbergen, and in Triassic and younger sediments in Europe (Cappetta 1987). Some ichthyosaur vertebrae have been assigned to *Mixosaurus*, a primitive, very widely distributed form also known from Alaska, China, Italy, ?Nevada, Spitsbergen, Switzerland and Timor (McGowan 1978). Articulated ichthyosaur skeletal material has been reported in the Schei Point Formation on Ellesmere Island by A.F. Embry (personal communication, 1988).

A second vertebrate locality was discovered by the Belcher Expedition in 1853 on Cameron Island, at the northwestern end of the Bathurst Group. The specimen consists of a single cervical vertebra (*Arctosaurus*), once thought to be dinosaurian but more recently considered to have belonged to a trilophosaur (D. Baird in Russell 1984, p. 9). It was probably derived from continental sediments of late Triassic age (?Heiberg Formation, personal communication, E.T. Tozer 1988; for locality see Tozer 1963, p. 645). Over 20 years after the recovery of the Cameron Island trilophosaur (Figure 2), the remains of Mesozoic vertebrates were discovered in southern Canada (Russell, L.S. 1966, p. 5).

In 1985, S.R. Ash discovered vertebrae, probably belonging to a small ichthyosaur, and ribs of a larger animal in the Blaa Mountain Formation on western Ellesmere Island. The unit is of middle to late Triassic age (Anisian to Karnian, cf. Balkwill 1983, p. 13).

Vertebrates of middle to late Triassic age from Alaska include paleoniscoid and coelacanth fishes, and *Mixosaurus* (Davies 1987; McGowan 1978). What little is known of Triassic vertebrates from Arctic Canada suggests that they were broadly distributed around the globe. There is nothing in either their taxonomy or their morphology that is inconsistent with the inference drawn by Balkwill *et al.* (1983), on the basis of fluviatile

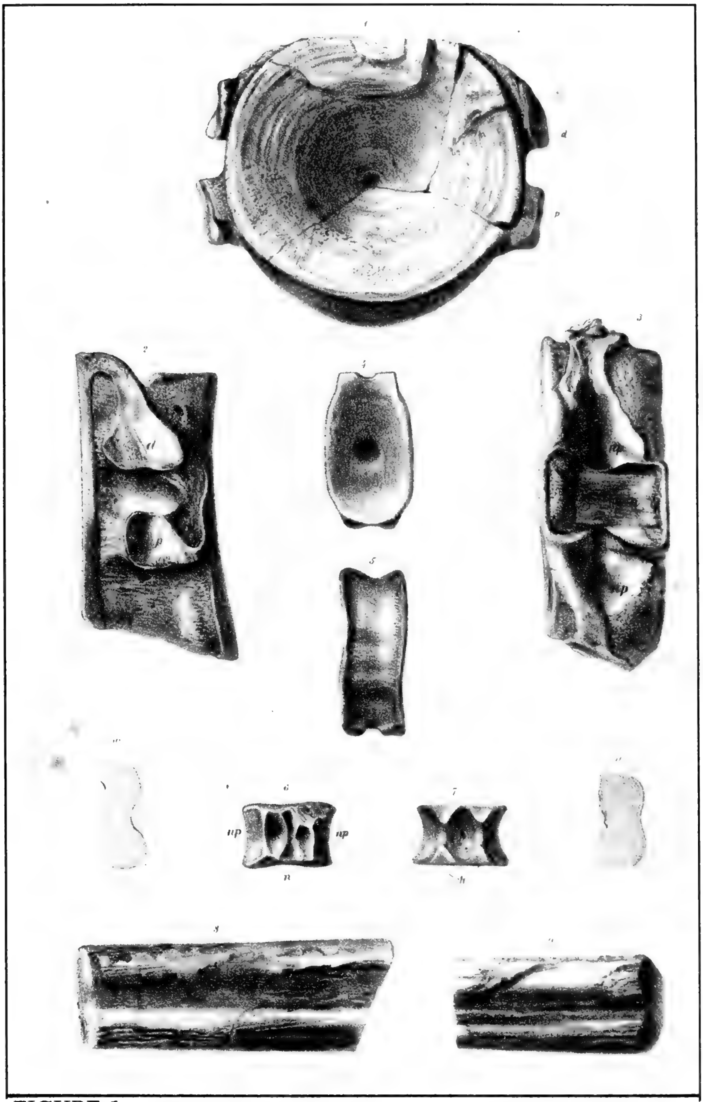

FIGURE 1: Remains of ichthyosaur vertebrae and ribs from Exmouth Island (between Cornwall and Devon islands) submitted to Professor Richard Owen by Captain Sir Edward Belcher (Owen 1855). These were the first remains of Mesozoic fossil vertebrates recovered from the Arctic Islands and Canada.

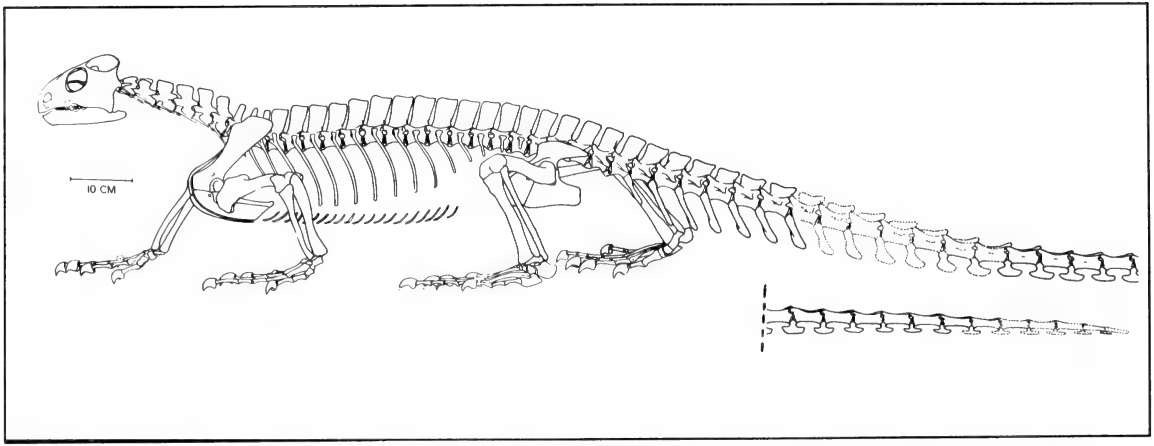

FIGURE 2: A skeletal reconstruction of the medium-sized reptile Trilophosaurus buettneri Case in a walking pose (Gregory 1945). A neck vertebra of a trilophosaur (Arctosaurus) of possible late Triassic age was collected from Cameron Island in 1853. (Posterior tail vertebrae were cropped and inset below to give a clearer idea of the length of the animal).

red-beds and marine limestones, that the regional climate was hot and seasonally arid during middle and late Triassic time.

JURASSIC OCCURRENCES

All of the Jurassic vertebrate records cited here represent marine animals collected from sediments of middle to late Jurassic (Bajocian to Volgian) age. Except where noted, the occurrences are listed in Russell (in press, B). Ichthyosaur fossils are relatively common, and have been found on Axel Heiberg, Cameron (Tozer 1963, p. 645), Ellef Ringnes, Mackenzie King, Melville and Prince Patrick islands. The genus *Ophthalmosaurus* has been identified on several of these islands, and is also known to occur in Argentina, England, France and the western United States (McGowan 1978, 1983, p. 165). An associated skeleton found on Melville Island belonged to a specimen estimated to have been 6.5 m long. Near this specimen both topographically and stratigraphically, was the skeleton of a cryptoclidid plesiosaur, which closely resembles contemporary specimens described from Spitsbergen and England. Another Jurassic plesiosaur occurrence has been documented on the North Slope of Alaska (Davies 1987).

EARLY CRETACEOUS OCCURRENCES

Only a few vertebrate specimens of this age are known from Arctic Canada. Plesiosaur material has been identified from marine strata (Christopher Formation, of Aptian-Albian age; Balkwill 1983) deposited on Melville and Mackenzie King islands. This has been identified by W. Langston (Tozer and Thorsteinsson 1964, pp. 159, 162), respectively, as elasmosaurid and polycotylid.

Early Cretaceous dinosaur footprints (iguanodont and carnosaur) have long been known to occur on Spitsbergen (Edwards *et al.* 1978). Sediments of the same age and lithology on Axel Heiberg Island (Isachsen Formation, personal communication, A.F. Embry, 1988; Valanginian to Barremian,Balkwill 1983) were examined in the course of The Dinosaur Project (China, Canada, Alberta) during the summer of 1986, but no footprints or any other

vertebrate fossils were discovered. Footprints of small theropod and ornithopod dinosaurs and birds, as well as dinosaur skin impressions, are known to occur in slightly younger sediments (Albian-Cenomanian) on the North Slope of Alaska (Davies 1987). An Alaskan turtle specimen may be of paleogeographic interest in that it apparently shows resemblances to early Cretaceous terrestrial turtles from Asia (Parrish *et al.* 1987).

LATE CRETACEOUS OCCURRENCES

Remains of marine vertebrates are relatively common in late Cretaceous (Santonian to Maestrichtian) sediments (Smoking Hills and Mason River formations, and equivalent strata) near the Beaufort Sea coast in the District of Mackenzie, and on Banks and Eglinton islands. A diverse fauna of fishes (including acipenserids, crossognathids, ichthyodectids, cimolichthyids, pachyrhizodontids, enchodontids, dercetids), plesiosaurs (elasmosaurids and cimoliasaurids), mosasaurs and toothed birds (hesperornithiforms) has been identified in these strata. The same fauna probably also occurs on northern Banks, Amund Ringnes, Ellef Ringnes and Ellesmere islands, where strata of similar age (Kanguk Formation, Cenomanian through Campanian) have yielded material belonging to ichthyodectid, osmeroidid, salmoniform and enchodontid fishes and undetermined plesiosaurs (Russell, in press A, and references cited therein). Shark teeth and hesperornithiform bones are also known to occur in contemporaneously deposited strata on the North Slope of Alaska (Davies 1987).

All of these marine vertebrates are known to occur in low-latitude seas (Russell, in press A), indicating that high-level predators in both regions were integrated into a single ecological unit of hemispheric proportions. It is reasonable to suppose that seasonal changes in temperature and daylength produced north-south migrations in these predators. They, however, represent but a fraction of the total diversity of marine vertebrates inhabiting low-latitude seas. It is interesting to note that, at least during early Cretaceous time, boreal marine-invertebrate assemblages were characterized by a lack of diversity and taxonomic separation from their low-latitude counterparts (Balkwill *et al.* 1983, p. 26; Jeletzky 1984). Marine vertebrates may have been less sedentary.

Remains of late Cretaceous (Campanian-Maestrichtian) dinosaurs have recently been described from the North Slope of Alaska, and discussed in the context of theories of

dinosaurian extinction (Brouwers *et al.* 1987; Davies 1987; Parrish *et al.* 1987). So far teeth and bones belonging to troodontids (small, large-brained carnivorous dinosaurs), tyrannosaurids, hadrosaurine and possibly lambeosaurine hadrosaurs (personal communication, J.R. Horner, 1988) and ceratopsids have been identified. Dinosaurian diversity seems high in view of the currently small sample-sizes, and, on the basis of similarities in the Asian and North American record in lower latitudes, perhaps at least protoceratopsid and ankylosaurid remains will one day be found on the late Cretaceous Alaskan land bridge between the two continents.

As in the case of contemporary high-latitude marine vertebrates, no indigenous element is, so far, evident in the Alaskan dinosaur assemblage. It is difficult to imagine a geographic situation more conducive to north-south seasonal migration in terrestrial vertebrates than the north-south orientation of the narrow Cordilleran region of North America during Cretaceous time (cf. Zeigler *et al.* 1985, Figure 6). Although many subadult hadrosaur specimens have been recovered from an Alaskan bone-bed (Davies 1987), none belongs to infantile specimens such as have been collected far to the south in Montana (Horner 1984). It is tempting to speculate that some hadrosaurs nested in mid-latitudes, and brought their young north with the flush of high-latitude vegetation in the spring. It is doubtful that all of the Alaskan dinosaurs remained at paleolatitudes of 70-85° throughout the year. Winter darkness was a certainty, and paleobotanical evidence suggests that frosts probably occurred as well (Galbreath *et al.* 1988, Wolfe and Upchurch 1988).

FIGURE 3: Dale Russell proudly displays the first dinosaur bone (an upper hindfoot bone of a juvenile hadrosaur) from the Canadian Arctic Islands.

The metatarsal of a juvenile hadrosaur has recently been collected from terminal Cretaceous (Maestrichtian) sediments on Bylot Island, near northern Baffin Island (Figure 3). Joshua Enookalook, a member of Elliot Burden's field party (Memorial University of Newfoundland) found the specimen in July 1987. The locality lay slightly south of the Alaskan North Slope localities during Cretaceous time (it is north of them now), at a paleolatitude comparable to those of ceratopsian and hadrosaur sites in the District of Mackenzie and the Yukon Territory (Russell 1984). Local climates may have been further ameliorated by the nearby presence of a Cretaceous Gulf Stream (Wolfe and Upchurch 1987, p. 47). Teeth of a mitsukurinid shark (*Scapanorhynchus*) and mosasaur vertebrae have also been recovered from marine sediments of approximately the same age on Bylot Island.

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Illustrated by Brenda Carter

TERRESTRIAL VERTEBRATES FROM THE TERTIARY OF CANADA'S ARCTIC ISLANDS

Mary R. Dawson[1]

Abstract: The only known Arctic terrestrial vertebrates of Tertiary age come from Ellesmere, Axel Heiberg, and Devon islands. Two ages are represented, early Eocene and early Miocene.

The Eocene faunas are most closely allied to others from North America, but also have strong affinities with Europe and some similarities to Asia. The known fauna inhabited delta plains and river margins in coastal areas. Representatives of 29 families, including bony fishes, amphibians, reptiles, birds, and mammals are known; best represented are turtles, crocodilians, and, among the mammals, dermopterans, pantodonts, and perissodactyls. Some members of the Eocene fauna, especially the tortoise, varanid lizard, crocodilian, primates, and dermopterans, suggest (as do associated plant remains) that their habitat included a warm-temperate climate. A polar light-regime, with dark winters and light summers, also prevailed. These environmental conditions may have served both as a limiting factor to the kinds of animals in the fauna, as well as a stimulus to produce specific adaptations to these conditions.

The Miocene fauna is from a peculiarly restricted site: lake-sediments preserved in a meteorite impact-crater. Floral remains suggest cool-temperate, probably coastal, climatic conditions. The fauna, consisting of two taxa of fishes, a swan, and four taxa of mammals, shows both North American affinities (heterosoricine shrew and primitive leporid) and endemism (rhinocerotid and artiodactyl).

Résumé: Les seuls vertébrés terrestres arctiques datant de l'époque tertiaire que l'on connaisse proviennent des îles Ellesmere, Axel Heiberg et Devon. Deux époques, l'Éocène inférieur et le Miocène inférieur, y sont représentées.

Les faunes de l'Écoène, qui s'apparentent étroitement à d'autres provenant de l'Amérique du Nord, ont également de profondes affinités avec celles de l'Europe et quelque similarité avec celles de l'Asie. La faune connue habitait dans les deltas et au bord des rivières dans les régions côtières. Des représentants de 29 familles sont connus et comprennent des poissons osseux, des batraciens, des reptiles, des oiseaux et des mammifères; les mieux représentés sont les tortues et les crocodiliens et, parmi les mammifères, les dermoptères, les pantodontes et les périssodactyles. Quelques membres de la faune de l'Éocène, particulièrement la tortue, le lézard varanidé, les crocodiliens, les primates et les dermoptères permettent de supposer (tout comme les restes de plantes qui les accompagnent) que leur habitat comprenait un climat tempéré chaud, de même qu'un régime d'éclairement polaire, fait d'hivers sombres et d'étés clairs. Ces conditions environnementales peuvent avoir servi soit de facteur limitant pour les animaux de la faune, soit de stimulus vers des adaptations spécifiques à ces conditions.

INTRODUCTION

Fossiliferous non-marine rocks of Tertiary age, the interval between about 65 and 2 million years ago, are present in a number of areas around the Arctic. Characteristically, these rocks contain a good record of fossil plants, but until 1975 none had yielded a record of contemporary land vertebrates. Now however, Canada's Arctic Islands have the unique distinction of providing the only known evidence of land animals that lived at high latitudes during two time intervals in the Tertiary. These two windows on the past, one in the early Eocene between about 50 and 55 million years ago, and the other in the early Miocene about 23 million years ago, are provided by deposits on Ellesmere, Axel Heiberg, and Devon islands (Figure 1). Although Arctic faunal history is woefully incomplete, these

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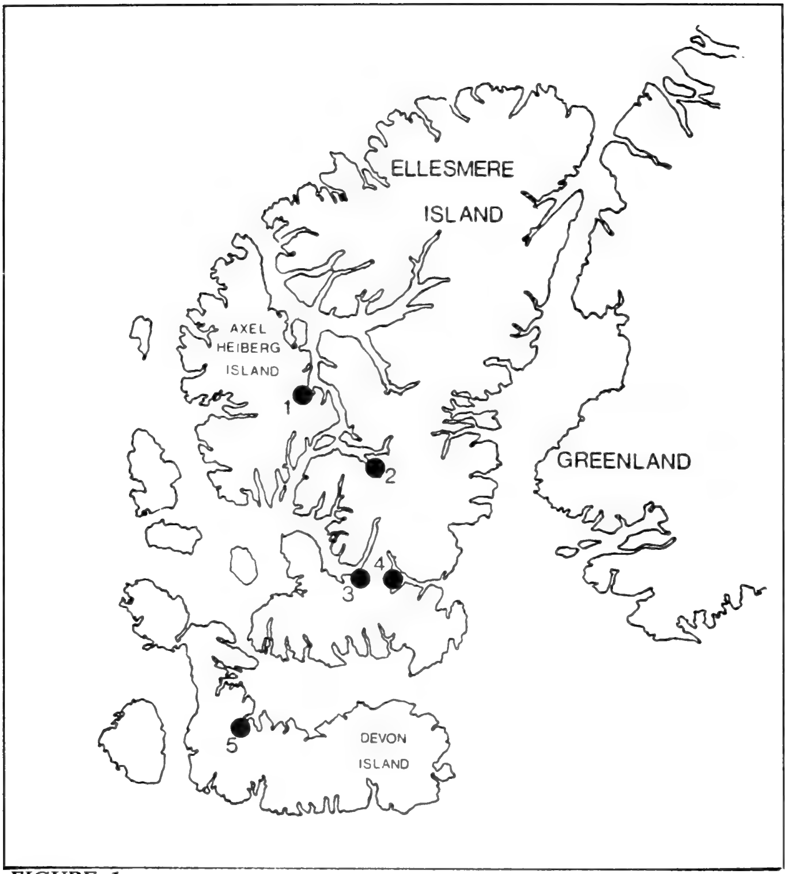

FIGURE 1: Distribution of terrestrial vertebrate - bearing localities of Tertiary age on Ellesmere, Axel Heiberg, and Devon islands; 1. Mokka Fiord; 2. Bay Fiord-Strathcona Fiord; 3. Stenkul Fiord; 4. Swinnerton Peninsula; 5. Haughton Astrobleme.

vertebrate records begin to form a picture of evolutionary and environmental features of high-latitudes before the Pleistocene - especially when combined with increasingly complete records of fossil plants.

TERRESTRIAL FOSSILS OF TERTIARY AGE IN THE ARCTIC

Among the many Tertiary rock units in northern polar regions, fossil plants are known from northern Siberia, northern Alaska, the Mackenzie Delta, Spitsbergen, Greenland, and the Canadian Arctic Archipelago (Axelrod 1984, and references cited therein). Fossil plants were found by earlier explorers of the Arctic Islands, especially in the widely distributed late Cretaceous to Eocene (and possibly Oligocene) Eureka Sound Group, in which well preserved wood and leaves were reported by Greely and Schei, among others (Troelsen 1950). More recent studies have augmented the known Eureka Sound macroflora and added a good palynological record (Hickey *et al.* 1983; Miall 1986; Ricketts 1986; Ricketts and McIntyre 1986). The younger (?Oligocene to Pliocene) Beaufort Formation, first described from Prince Patrick Island (Tozer 1956), and now recognized across the archipelago, contains fossil wood, leaves, seeds, and pollen (Matthews 1987; Matthews *et al.* this volume). These plant remains indicate that during the Tertiary the Arctic was far different from today: the floras of the Eureka Sound Group contain a rich record of the large deciduous gymnosperms *Metasequoia* and *Glyptostrobus*, other trees including *Betula*, *Cercidiphyllum*, and *Platanus*, a variety of understory ferns and other plants, *Equisetum*, and aquatics such as *Salvinia* and the lotus *Nelumbo*. Presence of plants whose modern relatives flourish only where freezing temperatures are rare or absent indicate that there were warm-temperate climatic conditions at the time of deposition. Floras from the younger Haughton and Beaufort formations contain trees and other plants that document cooler climates. The Beaufort Formation contains evidence of floral changes indicative of progressive climatic cooling through its temporal range (Matthews, *et al.* this volume).

Terrestrial vertebrates are less widespread in the Arctic Tertiary. Where they occur in Eocene and Miocene deposits in the Arctic Islands, they are associated with good records of fossil plants. Both lines of evidence can be used to reconstruct their high latitude habitats.

THE EOCENE VERTEBRATE RECORD

Four exposures of the Eureka Sound Group have produced terrestrial fossil vertebrates (Figure 1). Three are on central Ellesmere Island: Bay Fiord-Strathcona Fiord, discovered in 1975 (Dawson *et al.* 1976); Stenkul Fiord, discovered in 1982; and Swinnerton Peninsula, discovered in 1984. The fourth area is along Mokka Fiord, eastern Axel Heiberg Island, discovered in 1987. These localities occur between 77° and 79° 45'N. In every case, the fossils occur high in the Eureka Sound Group, in the Margaret and Mokka Fiord formations of Miall (1986), which are at least partly equivalent to the Iceberg Bay Formation of Ricketts (1986). Interbedded sandstones, siltstones, mudstones and coals characterize the fossiliferous parts of the group. Fossils occur both in fine-grained siltstones, where aquatic forms tend to be predominant, and in sandstones, especially those with ironstone nodules, where land mammals are more frequent. Rocks suggest coastal delta plains, river borders, and coal swamps; the fauna reflects this habitat in having many aquatic lower vertebrates (Figure 2).

Although taxonomic assignments of members of the Eureka Sound fauna, especially the mammals, are still preliminary, Table 1 gives an idea of faunal composition. Two faunal levels have been recognized, but only an emydid turtle, a taeniodont and a brontothere have been found in the uppermost level. The age of the two faunal levels can be estimated by biostratigraphic methods, although the lower level contains a mix of vertebrate temporal ranges not encountered in more southerly land-mammal assemblages. The lower fossiliferous level is probably early Eocene, and the upper level, early Bridgerian (middle Eocene). These are not precise assignments, but all that are warranted at this stage.

Prior to discovery of this high latitude fauna, plate-tectonics as well as faunal composition from mid-latitudes had provided evidence for an early Eocene land-connection between North America and Europe across the North Atlantic (McKenna 1975). The Arctic fauna corroborates this connection (West *et al.* 1977). Geographic affinities of members of the Eureka Sound faunas are preponderantly North American, all families being shared. Outside of their occurrence in the Eureka Sound Group, the salamander *Piceoerpeton*, the kinosternid, the plagiomenids, and *Lambdotherium* are known only from North American mid-latitudes. With those exceptions and the endemic forms discussed below, all faunal elements except the anosteirine and the taeniodont (Asian connections must be sought for

FIGURE 2: A landscape in the early Eocene showing some flora and fauna of the Eureka Sound Group on Ellesmere Island. In a deltaic habitat near a stand of dawn redwoods (Metasequoia), the large pantodont (Coryphodon) eats lotus (Nelumbo). A small alligator (Allognathosuchus) and soft-shelled turtles (Trionyx) occupy the foreground. Perissodactyls (Hyrachyus) browse in the middle distance. Reconstruction by Clifford J. Morrow, Jr.

TABLE 1: EUREKA SOUND FAUNAL LIST.[1]

- Class Osteichthys
  - Family Lepisosteidae
    - ?*Lepisosteus* sp.
  - Family Amiidae
    - *Amia fragosa*
    - *Amia* cf. *A. uintaensis*
  - Family Esocidae
    - *Esox* sp.
- Class Amphibia
  - Family ?Scapherpetontidae
    - *Piceoerpeton* cf. *P. willwoodense*
- Class Reptilia
  - Order Testudinata
    - Family Emydidae (abundant; both levels)
      - two emydines, genus and species unidentified
      - emydine unidentified
    - Family Testudinidae
      - *Geochelone* sp.
    - Family Kinosternidae
      - kinosternine genus and species unidentified
    - Family Carettochelyidae
      - anosteirine genus and species unidentified
    - Family Trionychidae (abundant)
      - *Trionyx* sp.
      - cryptodire genus *incertae sedis*
  - Order Squamata
    - Family Anguidae
      - glyptosaurine genus and species unidentified
      - subfamily *incertae sedis*
    - Family Varanidae
      - genus and species unidentified
    - Family Boidae
      - erycine unidentified
  - Order Crocodilia
    - Family Crocodylidae
      - *Allognathosuchus sp.* (abundant)
- Class Aves
  - Order Diatrymiformes
    - Family Diatrymatidae
      - *Diatryma* sp.
  - Order Charadriiformes
    - Family Presbyornithidae
      - *Presbyornis* sp.
- Class Mammalia
  - Order Multituberculata
    - Family Neoplagiaulacidae
      - *Neoplagiaulax* sp.

TABLE 1: (concluded)

Order Leptictida
    Family Leptictidae
        species undetermined
Order Pantolesta
    Family Pantolestidae
        cf. *Pantolestes* and *Chadronia*
Order Primates
    Family Paromomyidae
        new genus and species
        new species
Order Dermoptera (abundant)
    Family Plagiomenidae
        cf. *Plagiomene*, 4 or 5 species
Order Rodentia
    Family Ischyromyidae
        3 species
Order Taeniodonta
    Family Stylinodontidae
        genus undetermined (upper level)
Order Pantodonta (abundant)
    Family Coryphodontidae
        Coryphodon sp.
Order Acreodi
    Family Mesonychidae
        cf. *Mesonyx* spp.
Order Creodonta
    ?Family Hyaenodontidae
        genus undetermined
        Prolimnocyon sp.
Order Carnivora
    Family Miacidae
        Viverravus sp.
        miacine cf. *Uintacyon* and *Vulpavus*
Order Perissodactyla (abundant)
    Family Hyrachyidae
        Hyrachyus sp.
Family Brontotheriidae
        ?*Lambdotherium* sp.
        cf. *Manteoceras* sp. (upper level)

[1] Identifications from Estes and Hutchison (1980), McKenna (1980), with additions from later field work.

these) are shared with Europe. Several other faunal elements are also shared with Asia. In total, the Eureka Sound fauna probably was not geographically isolated but occupied part of a vast Holarctic biogeographic province.

Some of the Arctic fauna, notably the unidentified cryptodire, the species of *Allognathosuchus*, and the diversity of plagiomenids, appear to have been endemic to the Arctic. Such endemism may be related to limiting environmental conditions, in which warm climates were coupled with the characteristic polar light-regime featuring continuous darkness from about mid-November until mid-February and continuous light from roughly May until mid-August. That such high-latitude light conditions would have prevailed has been shown by paleomagnetic work demonstrating that, during the Eocene, Ellesmere and Axel Heiberg islands were situated well within the Arctic Circle, slightly less than 3° farther south than their present latitudes (McKenna 1983). This is not a significant difference from today in terms of polar light-regime. Seasonality, which in this case would be light-dark, not warm-cold induced, is indicated both by marked growth rings in fossil wood from the Eureka Sound Group and by growth rings in some of the bones of the large salamander, *Piceoerpeton*.

The fossil-plant evidence for warm climatic conditions is strongly supported by the terrestrial vertebrates: the large, non-burrowing tortoise *Geochelone*, the varanid lizard, and the alligator *Allognathosuchus* indicate that freezing temperatures were not characteristic of the habitat. Among the mammals, the closest modern relatives of the primates and dermopterans inhabit tropical regions.

Because the Arctic Eocene combination of warm temperatures and polar light conditions does not exist today, it is difficult to interpret animal and plant responses to these extinct environmental conditions. All trees from the Eureka Sound deposits are deciduous, possibly an adaptation to the absence of sunlight in the polar winter (personal communication, Leo J. Hickey). Low diversity of the fauna, compared to Eocene mid-latitude assemblages (West *et al.* 1977; McKenna 1980), suggests that the environment was stressful. Absence of contemporary groups well-represented farther south, such as marsupials, diverse primates, condylarths and artiodactyls, also indicate limiting factors.

Vertebrate responses to the dark winters were probably varied. Migration might have been an option for the large herbivore *Coryphodon*, and some carnivores might have followed this prey. The smaller mammals, the amphibians and reptiles probably did not

leave the Arctic in the winter, and dormancy or hibernation might have been practised by some of them (Estes and Hutchison 1980). Other Arctic Eocene animals probably survived the dark winter by feeding on dry fruits, seeds, roots and tubers. One of the turtles in the fauna, the endemic cryptodire, was a mollusc-eater, a food supply that would have been available year around (Estes and Hutchison 1980). Development of nocturnality might have been a useful Arctic specialization.

The case of the plagiomenid dermopterans is interesting. Relatively rare in mid-latitude North American Eocene deposits, they are the most abundant and diverse small mammals in the Arctic Eocene, represented by about five species. Clearly the plagiomenids were well adapted to this habitat, possibly finding homes in the extensive forests (Figure 3). Their diversity might reflect a relatively recent colonization of the area, accompanied by a radiation into fresh niches.

While much remains to be explained about high-latitude evolutionary developments in the Eocene, the fauna of the Eureka Sound Group provides concrete evidence not only that polar regions were habitable, but also that they nurtured a fauna unlike any other. Except for this glimpse, vast stretches of the northern Holarctic provide no known Eocene terrestrial fossil vertebrates. The closest comparable record is from much farther south (about 50°N) in the London Basin.

THE MIOCENE VERTEBRATE RECORD

The only known arctic Miocene terrestrial vertebrates occur in Haughton Astrobleme, a nearly circular meteorite impact-crater about 20 km in diameter, located at 75° 22'N, near the north-central coast of Devon Island (Figure 1). The impact that formed the crater has been dated at between 22 and 23 million years (22.4 ± 1.4 million years ago by the fission-track method (Omar *et al.* 1987); and 23.4 ± 1.0 million years ago by ^{40}Ar-^{39}Ar analysis (Jessberger 1988)). These dates fall at the beginning of the early Miocene and can be used to mark the beginning of a lake that developed in the crater soon after it formed. The vertebrate fossils, with associated pollen and megaflora, occur in remnants of sediments deposited in the lake - the Haughton Formation (Frisch and Thorsteinsson 1978; Hickey *et al.* 1988).

FIGURE 3: Plagiomenid dermopterans, the most abundant small mammals in the Eureka Sound fauna, are probably related to modern "flying lemurs". This reconstruction suggests similar gliding adaptations in the Ellesmere Island Eocene plagiomenids. They are shown in an Eocene Cercidiphyllum tree, remains of which occur frequently with fossil vertebrates in the Eureka Sound Group. Reconstruction by Clifford J. Morrow, Jr.

Vegetation during deposition of the Haughton Formation consisted of a mixed conifer-hardwood forest dominated by the conifers *Pinus*, *Tsuga*, and *Larix*, and the hardwoods *Betula*, *Alnus*, and *Corylus*. Ericaceous pollen is abundant in the formation, suggesting presence of boreal heath. Cool-temperate conditions in a coastal habitat are indicated by the total flora (Hickey *et al.* 1988; Barnosky and Dawson, in press).

Vertebrates from the Haughton Lake deposits include two kinds of salmoniform fishes: a trout (*Eosalmo* sp.) and a smelt-like fish (cf. *Osmerus* sp.). One bird, a swan (Tribe Cygnini) is present. Mammals include: a shrew (Heterosoricinae); a primitive rabbit (Leporidae); primitive rhinoceros (Rhinocerotidae); and an artiodactyl of uncertain affinities. Many rabbit specimens are known, but the other taxa are rare. The rhinoceros is represented by a nearly complete, though broken, skeleton.

None of the members of this vertebrate fauna shows close affinities with the previously mentioned Eocene Eureka Sound fauna: this might not be expected in light of seemingly small temporal and climatic differences. Perhaps the highly-distinctive morphologies of the Haughton rhinoceros and artiodactyl indicate that some environmental or geographic isolating mechanism separated the Devon Island fauna from others, and had done so for some time. Lancaster Sound may have become an effective, open-water barrier to north and south movements of terrestrial vertebrates.

This vertebrate assemblage has some paleoenvironmental significance. For example, trout and smelt are northern cool-water fishes. Today swans do not occur as far north as Devon Island, again suggesting that the Miocene was milder than present. The mammals are less indicative of climate.

CONCLUSIONS

The extinct Tertiary environments now known from Canada's Arctic have produced unique floral and faunal developments in an area that had particular environmental conditions. The Eocene vertebrate fauna was not geographically isolated, but had a unique composition probably due to limiting environmental conditions. Evolutionary innovations among the Arctic vertebrates may have proved adaptive farther south as the climate cooled later in the Tertiary.

The Miocene vertebrate record does not represent a normally-balanced fauna. Endemism in that fauna suggests that it developed following a period of geographic isolation.

Neither Eocene nor Miocene faunas show connections to the modern Arctic terrestrial vertebrate faunas, which developed following the complex biotic remodelling of the Pleistocene.

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Illustrated by Brenda Carter

PLANT AND INSECT FOSSILS FROM THE LATE TERTIARY BEAUFORT FORMATION ON PRINCE PATRICK ISLAND, N.W.T.

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Abstract: The late Tertiary Beaufort Formation, which is exposed on many of the western islands of the Canadian Arctic Archipelago, contains well preserved plant and insect fossils. This paper is a preliminary report on new finds from Prince Patrick Island. Organic deposits from 14 sites have been studied. The fossils discussed here come primarily from one, Devaney Section 1, which is located near the site where the Beaufort Formation was first defined.

At least 96 species of vascular plants, 49 species of bryophytes and 80 species of arthropods are listed. Some plant remains represent extinct genera (e.g. Epipremnum, Aracites), while many of the others may represent extinct species. Trees account for only about 11% of the flora (Pinus strobus type, Picea, Abies, Larix, Thuja, Betula and Populus); nevertheless Prince Patrick Island was probably forested at the time of deposition of these beds, with a mean July temperature at least 9°C warmer than present. In addition to Betula, Alnus, Cornus stolinifera and various Ericaceae, the shrub component of the flora contained taxa such as Decodon and Comptonia, which do not reach northern areas today, as well Weigela which is extinct in North America. The flora also includes typical arctic/alpine plants such as Oxyria, Dryas and Saxifraga oppositifolia. Most bryophyte fossils from Prince Patrick Island deposits represent species belonging to the circumpolar element of the modern moss flora.

The majority of insect fossils represent beetles that now live in stream-side communities. Some have been recorded from Meighen Island, but in general the Prince Patrick Island fauna is more similar to that seen in "upper Beaufort" deposits on northern Banks Island.

Despite some floristic differences, it has been argued on the basis of plant fossils that "upper Beaufort" floras from northern Banks, Prince Patrick and Meighen islands are all about the same age. If so, the latest information from Meighen Island (Foraminifera and Sr-isotope dates) means that they date to the Pliocene (probably early Pliocene) rather than late Miocene as previously thought.

Résumé: La Formation de Beaufort, qui date du Tertiaire supérieur et affleure dans maintes îles de l'ouest de l'Archipel arctique canadien, renferme des plantes et des insectes fossiles bien conservés. Le présent article est un rapport préliminaire sur les découvertes récentes faites dans l'île Prince Patrick. Les gisements organiques de 14 sites ont été étudiés. La majorité des fossiles analysés ici proviennent de la coupe Devaney 1, située près du site où la Formation de Beaufort a initialement été définie.

Au moins 95 espèces de plantes vasculaires, 49 espèces de bryophytes et 80 espèces d'arthropodes sont représentées. Certains reste végétaux appartiennent à des genres aujourd'hui disparus (par ex. Epipremmum, Aracites), et de nombreux autres, à des espèces disparues. Les arbres ne comptent que pour 11 % environ de la flore (Pinus strobus, Picea, Abies, Larix, Thuja, Betula et Populus); néanmoins, à l'époque de la mise en place de ces gisements, l'île Prince Patrick était probablement recouverte d'arbres et la température moyenne en juillet était supérieure de 9°C au moins à celle d'aujourd'hui. Outre Betula, Alnus, Cornus stolinifera et quelques Éricacées, la flore arbustive incluait des taxons tels que Decodon et Comptonia, aujourd'hui disparus des régions septentrionales, ainsi que Weigela que l'on ne rencontre plus en Amérique du Nord. La flore incluait également des plantes arctiques-alpines typiques telles que Oxyria, Dryas et Saxifraga oppositifolia. Presque tous les bryophytes fossiles présents dans les gisements de l'île Prince Patrick représentent des espèces du domaine circumpolaire de la flore hygrophile actuelle.

La plupart des insectes fossiles sont des coléoptères qui, de nos jours, vivent sur les rives des cours d'eau. Certains ont été apparentés à ceux de l'île Meighen, mais, en général, la faune de l'île Prince Patrick ressemble davantage à celle présente dans les gisements de la Formation de Beaufort, dans le nord de l'île Banks.

Malgré quelques différences floristiques, les flores de la Formation de Beaufort du Tertiaire supérieur des îles Banks, Prince Patrick et Meighen seraient à peu près contemporaines, comme l'indique l'étude des plantes fossiles. Si c'est le cas, les dernières données recueillies à l'île Meighen (datation au moyen des Foraminifères et du Sr isotopique) les feraient dater du Pliocène (probablement du Pliocène inférieur) plutôt que du Miocène supérieur comme on le pensait.

INTRODUCTION

The late Tertiary Beaufort Formation, which is exposed on many of the western Queen Elizabeth Islands (QEI) and on Banks Island (Figure 1), is a source of well-preserved plant and insect fossils (Hills 1975; Matthews 1977A). It consists mostly of alluvial sands

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containing detrital organic debris. Prior to this report, most collections of Beaufort Formation fossils were from widely separated exposures on northern and southern Banks Island and on Meighen Island (Hills 1975; Hills *et al.* 1974; Hills and Matthews 1974; Kuc and Hills 1971; Kuc 1973; Matthews 1977A, 1987A, 1989) (Figure 1). Except for the extensive data from Meighen Island and a brief reference by Hills (1975) to fossils from Prince Patrick and Ellef Ringnes islands little has been published, or indeed is known about the flora and fauna of the Beaufort Formation from the western QEI. Prince Patrick Island represents an especially embarrassing gap in our knowledge because it is the place where the Beaufort Formation was first recognized by Tozer (1956). This paper is intended as a step in redressing this problem. It lists and discusses the chronological and paleoenvironmental implications of plant and insect fossils from a few of the 56 sites visited and studied by one of the authors (J.G.F.) and Jon Devaney (then with the Geological Survey of Canada) during the summer of 1987.

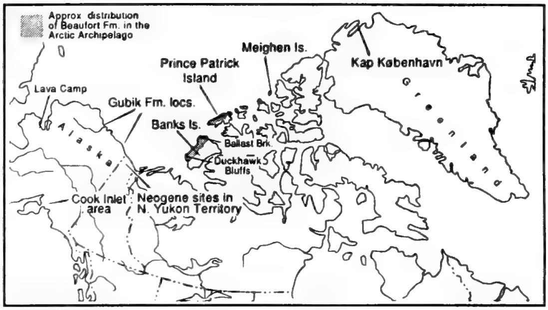


FIGURE 1: Late Tertiary sites mentioned in the text, including Beaufort Formation localities in the Arctic Archipelago.

THE BEAUFORT FORMATION ON PRINCE PATRICK ISLAND

The name Beaufort Formation was first used for unconsolidated, wood-bearing sands and gravels in the Mould Bay area of Prince Patrick Island (Figures 1,2) (Tozer, 1956). The strata making up this formation on Prince Patrick Island comprise a single lithostratigraphic unit characterized by recurring intervals of cross-bedded, medium to coarse sand and pebbly sand interspersed with subsidiary amounts of gravel, rippled and horizontal fine sand, silty or clayey "mud", wood-beds and beds of fine plant detritus interlayered with fine sediments (Figure 3). The sediments represent an unlithified, sandy, braided river deposit - the coarse sediments being channel and bar deposits while the finer and wood-bearing strata are low-stage overbank deposits (Fyles, unpublished abstract 1987; Devaney and Fyles 1988).

These deposits form a wedge, elongated northeast parallel to the length of the island (Figure 2), which thickens to the northwest and presumably extends offshore beneath the Arctic Ocean. The braided streams that deposited the Beaufort sediments appear to have flowed northwestward across the belt. The Beaufort Formation rests unconformably on Devonian to Cretaceous bedrock, and is capped disconformably by a thin unit of gravel (commonly with boulders) which forms an upland plain sloping downward to the northwest. The stratigraphic and sedimentological information presented above and the paleontological information presented below refer almost entirely to the thin, southeastern margin of the Beaufort belt on Prince Patrick Island, where almost all the good stream-cut exposures occur. As yet, very little is known about the thick Beaufort deposits beneath the western part of the island.

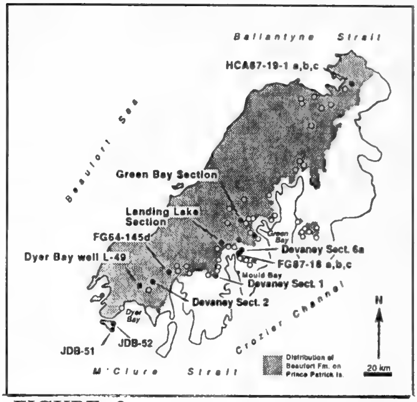


FIGURE 2: Prince Patrick Island showing sites visited and studied by Fyles and Devaney in 1987. Black dots indicate sites from which fossils have been isolated (as of May 1988). Stippling indicates areas where Beaufort Formation outcrops.

Most of the fossils discussed here come from the finer detrital facies found in both cross-stratified and horizontally-bedded sequences. They occur either as wood and fine detritus in sand and silt, or as mats of moss-rich detritus. None of the Prince Patrick exposures examined to date has revealed autochthonous peats or forest-beds with tree stumps in growth position (Fyles, unpublished abstract 1987). The Landing Lake and Green Bay sites contain what appear to be autochthonous peat beds, but they may post-date the Beaufort Formation.

SAMPLE SITES

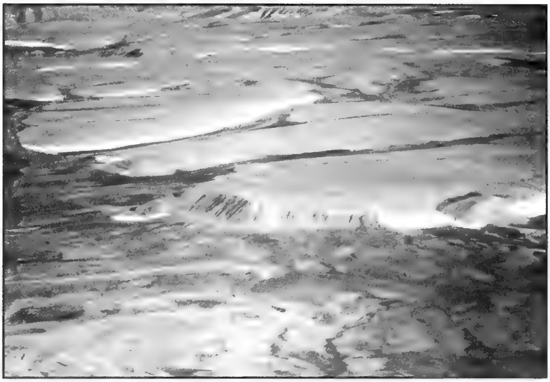
Virtually all of the sites examined by Fyles and Devaney contain plant macrofossils. Figure 2 shows sites (black dots) that have been studied to date. Only a few of the

FIGURE 3: The Beaufort Formation on Prince Patrick Island:

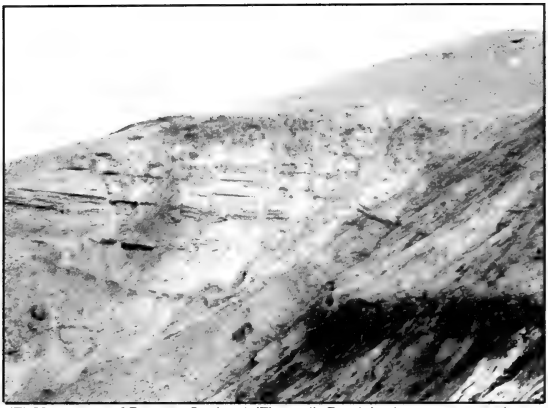
(A) Typical sorted woody-detrital bed containing flattened and rounded wood - not the best source of macrofossils.

(B) Unsorted, angular wood in silt at the level of sample JBD-12, Devaney Section 1 (Figure 4). This type of deposit may yield macrofossils.

(C) Fine plant-detritus layers in silt and fine sand. Sediments of this sort were the source of sample FG87-1e at Devaney Section 1 (Figure 4), and are the best type for delicate macrofossils, allochthonous mosses and pollen.



(D) Beaufort plain from the air showing typical sections in the centre and background.



(E) Upper part of Devaney Section 1 (Figure 4). Break in slope represents change from more organic sediments below and inorganic sand, with the break in slope being approximately at the level of sample JBD-12. Large dark area in right foreground is the 1 m thick horizon of woody beds and fine plant detritus with silt and fine sand at the base of the section (Figure 4).

(F) Downstream end of the Green Bay Section (Figure 5). The dark patch at river level (right centre) is the source of sample FG10a/b. Arrow indicates approximate position of the autochthonous moss-bed in the main part of the section.

samples currently under study are discussed here, and most of them (Tables 1-3) come from Devaney Section 1 (Figure 4), which is located near the area where Tozer (1956) first defined the Beaufort Formation. Section 1 is a composite of exposures, with about 40 m of Beaufort sediments extending over a lateral distance of approximately 200 m. One kilometre east of the site, the Beaufort Formation wedges out against the higher-standing upper Devonian sandstone.

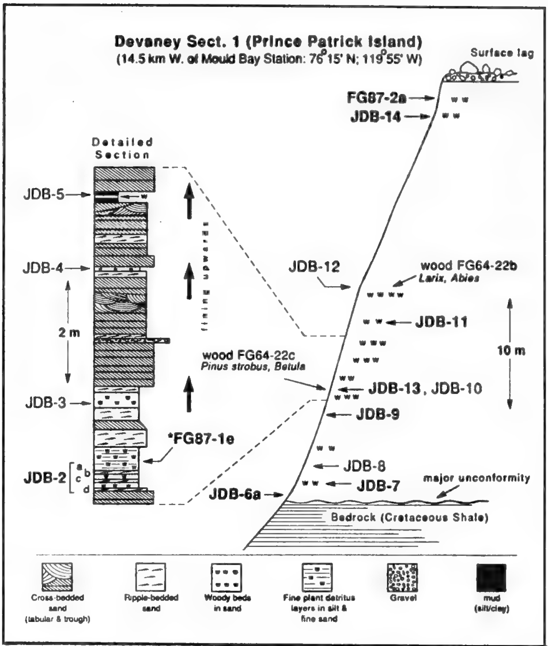


FIGURE 4: Devaney Section 1, showing stratigraphic details in part of the section and sources of samples collected. Those shown in bold have been examined for macrofossils. The sample with an asterisk has also been studied for fossil pollen (see text). Wood identifications are from R.J. Mott (unpublished Geological Survey of Canada Palynological Report 68-4).

Several Devaney Section 1 samples (JDB-2, JDB-13, JDB-10, FG87-1e) are from a 1 m thick sequence (Figure 3e) of fine plant detritus interlayered with medium to fine sand and silt with tabular, rippled and cross-bedded laminae. Sample FG87-1e, one of the richest in plant and insect fossils, and the only one from the section that was examined for pollen (R.J. Mott, unpublished Geological Survey of Canada Palynological Report 87-11) is from the upper part of this organic zone. Its macrofossils are pooled with those of sample JDB-13b from approximately the same level at another part of the section (see heading "13&1e", Table 1). FG87-2a ("2a" in Table 1) comes from a 10 cm peaty layer beneath the surficial bouldery gravel, and represents the highest organic horizon exposed at the section. JDB-6a ("6a" in Table 1) consists of detrital organic matter in sand less than 1 m above bedrock (Figure 4). A few wood samples have also been identified from this and adjacent sections (R.J.Mott, unpublished Geological Survey of Canada Palynological Report 68-4).

The section from which samples FG87-18 a,b and c come is a 15 m thick sequence resting on an eroded bedrock surface with at least 5 m of relief. The fossils are from a 1.5 m unit of silty sand, silt and fine sand with multiple layers of fine plant detritus which lie above the 2 m unit of coarse pebbly sand that forms the base of the Beaufort sequence at the site.

The Green Bay Section (Figures 2, 3F, 5), 51 m above sea level at its base, is 12 km northwest of Green Bay. It differs from the other sites discussed because its top is a bench located approximately 40 m below the regional Beaufort surface. It is also one of the few sections containing autochthonous peat; although, as indicated below, this peat and overlying sediments probably post-date the Beaufort Formation. FG10a/2, which has yielded a flora and fauna slightly different from other Prince Patrick Island Beaufort Formation sites, was collected approximately 150 m downstream at river level in as moss-rich lens of wood and fine plant detritus up to 1 m thick enclosed in medium sand.

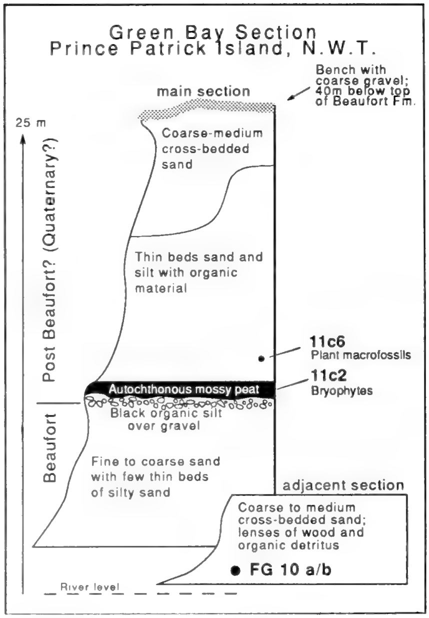


FIGURE 5: Generalized stratigraphy of the Green Bay exposure (Figure 3F) showing sources of samples FG10a/b and two samples from the autochthonous peat at the main section FG11c2 (Table 2) and the overlying peaty sediments (FG11c6).

The top of the Landing Lake Section (Figure 2) is also well below the Beaufort Formation surface, so it too might contain post-Beaufort sediments. The fossils come from a layer of moss-peat and enclosing sands with wood and other organic detritus. The moss-mat appeared in the field to be a fragment of a former surface layer that fell into a stream and subsequently was buried in the sandy alluvium. The mosses listed in Table 2 come from this autochthonous fragment; the vascular plants in Table 1 are from organic detritus in the enclosing sand. Note that Tables 1-4 are at the end of the paper.

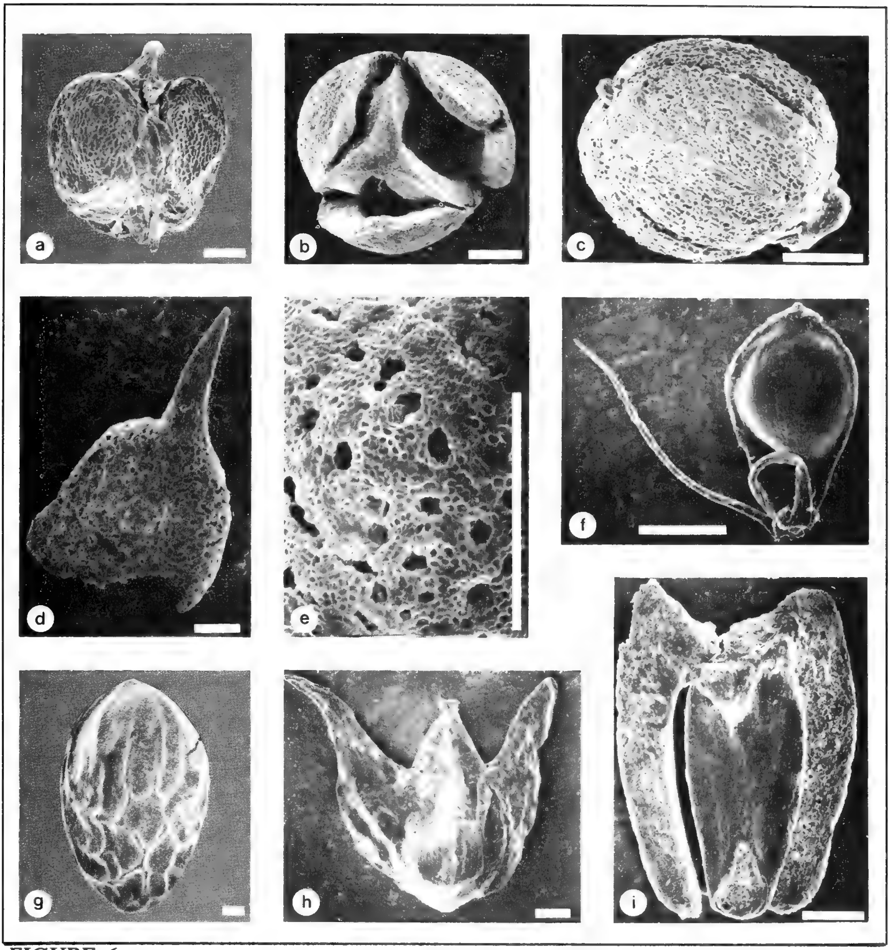


FIGURE 6: Electron Microscope images of plant macrofossils from the Beaufort Formation on Prince Patrick Island and related fossils. Scale bar=0.3 mm. (a) GSC-95881: Rumex sp., sample FG 87-18b. (b) GSC-95882: Paliurus sp. showing three open germination valves, sample MRA 7-25-80-2, Henderson Bluff, Alaska. (c) GSC-95883: Paliurus type, sample FG 88-53b, Ellesmere Island. The last two specimens are similar to, but better preserved than, those seen from Prince Patrick Island. (d) GSC-95884: fragment of unknown seed, sample FG 87-2a. (e) Detail of fenestrate surface of specimen GSC-95884. (f) GSC-95885: Rhynchospora capitellata (Michx.) Vahl., sample FG 87-2A. Note: the cap typical of Rhynchospora fruits is missing on this specimen, but a scar showing its former position is evident. (g) GSC-95887: Prunus sp., sample JDB-13b. (h) GSC-95886: Myrica cf. eogale Nikit., sample FG87-10a/2. (i) GSC-95888: Lycopus sp., sample FG 87-1e).

THE PRINCE PATRICK ISLAND BIOTA

Vascular Plants

Fourteen of the sites sampled by Fyles and Devaney have been studied for fossil plants and insects. Table 1 lists vascular plants from section FG87-18, several levels of Devaney Section 1, two parts of the Green Bay section and Landing Lake site (Figures 2, 3E, 3F, 4). Many of the fossils clearly refer to extant genera, and some cannot be separated from extant species; however, a final conclusion on the specific identify of the majority of the fossils must be deferred pending more detailed comparative studies. SEM micrographs of typical plant macrofossils are shown in Figure 6, and the distribution of selected taxa in Figure 7.

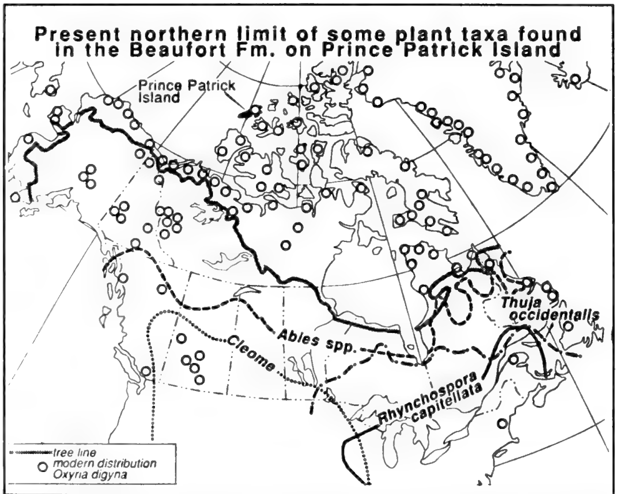


FIGURE 7: Northern distributional limits of selected vascular-plant taxa seen as fossils in the Beaufort Formation on Prince Patrick Island. Distribution of Abies and Thuja occidentalis after Hosie (1969); Cleome from Iltis (1957); Rhynchospora capitellata from Gale (1944); Oxyria digyna from Porsild and Cody (1980).

The samples from Devaney Section 1 contain a minimum of 64 taxa, of which approximately 11% are trees, 34% shrubs and 55% herbs. In spite of the low percentage of trees in the flora, the presence of large pieces of conifer wood (R.J. Mott, unpublished Geological Survey of Canada Palynological Report 68-4), conifer cones and abundant leaves of larch, spruce and pine (*Larix*, *Picea* and *Pinus*) indicate that the region was forested at the time of deposition. Most of the pine needles are of the five-needle white pine (*P. strobus*) type. Birch (*Betula*) nutlets are also abundant in many samples, and many are of the arboreal type. This suggests mixed coniferous/deciduous forests and a treeline at least 1,100 km north of its present position.

Supporting evidence of coniferous forests comes from preliminary pollen work by R.J. Mott (unpublished Geological Survey of Canada Palynological Report 87-11). It shows 7% spruce and 30% pine in sample 1e from Devaney Section 1. Larch pollen is rare to non-existent in the samples examined so far, but larch is often underrepresented in pollen spectra - in any case the presence of larch needles shows that the tree was growing in the region. Unlike pollen spectra from Duck Hawk Bluff on southern Banks Island, hardwood types such as hickory, walnut, elm, ash and maple (*Carya, Juglans, Ulmus, Fraxinus* and *Acer*) are missing from the Devaney Section 1 spectrum (R.J. Mott, unpublished Geological Survey of Canada Palynological Report 88-11). Hills (1975) reports a *Carya* nut from Prince Patrick Island but the location of his section and other details are not known to us. The Prince Patrick Island macrofossil assemblages discussed here lack several tree genera such as dawn redwood, China cypress, bald cypress, mulberry, tulip-tree and walnut (*Metasequoia, Glyptostrobus, Taxodium, Morus, Liriodendron* and *Juglans*) that are present in the Beaufort sediments at Duck Hawk Bluff on southern Banks Island (Figure 1).

The Prince Patrick Island pollen spectra do contain significant amounts of birch and alder (*Alnus*), which as indicated above, is matched by abundant macrofossils of these two plants. Some of the alder macrofossils are identical to fruits of *Alnus incana*, a species which currently grows near flood plains. Many of the same samples also contain coralloid actinorhizal root-nodules (Burgess and Peterson 1987) similar to those recovered from Quaternary deposits (White *et al.* 1985). They probably developed on the roots of the alders. Both arboreal and shrub-type *Betula* nutlets occur in most assemblages. One site yielded rare specimens of the large *Betula apoda*-type nutlets seen from Banks Island Beaufort Formation deposits, particularly at Duck Hawk Bluff (Matthews 1987A). They are poorly preserved and may have been rebedded from older deposits no longer exposed on the island.

Several samples contain leaves of avens (*Dryas*) and seeds indistinguishable from those of the common arctic-alpine mountain sorrel *(Oxyria digyna)* (Figure 9). FG-10a/2 also contained a few leaves of another common arctic plant, purple saxifrage *(Saxifraga oppositifolia)*. Rather than indicating an arctic environment, these fossils indicate that river floodplains in which the detritus accumulated were wide and only partly forested. This would also explain the high percentage of herbs in the flora. Many of them probably grew

on the floodplains and hence were more readily incorporated in alluvial detritus than plant remains from distal forest communities.

Of the shrubs and herbs listed in Table 1, most are presently components of the northern boreal flora, but a few such as *Cleome*, *Decodon*, *Verbena*, *Hypericum*, *Sambucus*, *Physocarpus*, and *Wiegela* do not currently have northern representatives (Figure 7). Their presence shows that the coniferous/deciduous forests on Prince Patrick Island, though probably similar in appearance to those within the boreal zone today, were floristically unique (Matthews 1987A).

With a few exceptions, the composition of most of the Prince Patrick Island macrofossil assemblages is similar. The presence of *Betula apoda*-type fossils in one sample has already been mentioned. The lowest sample of Devaney Section 1 (6a in Figure 4) differs from the others in the sequence by the presence of a few endocarps of *Comptonia*. The organic detritus from the Landing Lake site also contains rare endocarps of *Comptonia*, but more important it is one of the few samples from Prince Patrick Island to yield fruits of the extinct lythraceous plant *Microdiptera* (Tiffney 1981). *Microdiptera* is rather common in Beaufort samples from southern Banks Island (listed as *Mneme* sp. in Matthews 1987A, 1989). Seeds of *Cleome*, a rare element in most Banks Island Beaufort samples, were present in a few of the Prince Patrick Island samples (e.g. sample 9 at Devaney Section 1 and the Landing Lake sample - Table 1). The present North American distribution of the genus is in grassland and prairie regions (Iitis 1957) (Figure 7).

Sample 11c6 at the Green Bay Section (Figure 5) is radically different from typical Beaufort floras on the island. Plant macrofossils are rare, and, unlike virtually all of the other Prince Patrick Island samples, they represent species that are now typical of northern treeline and Low-Arctic tundra sites. Even before the fossils were studied, the fact that the sediments at the Green Bay Section seem to be *inset* in the Beaufort plain suggested that they might be younger than the Beaufort Formation. The vascular plant macrofossils from sample 11c6 and bryophyte fossils (FG11c2, Table 2) from an underlying autochtonous peat support this conclusion, as do preliminary pollen analyses (R.J. Mott, unpublished Geological Survey of Canada Palynological Report 87-11). However, the vascular plant fossils from sample FG10a/2 also show clearly that the basal part of the section is of Beaufort age.

The deposits at Landing Lake are also below the level of the Beaufort plain. The autochtonous moss-mat from that section differs in its moss flora from other Beaufort deposits (see below) and may also be pre-Beaufort. But if this is so, then the Tertiary fossils in the host sediments are rebedded (see below).

Sample FG-10a/2 from the Green Bay Section contains several taxa not seen in other samples, but this may be entirely a taphonomic bias (see below). Taphonomic factors and/or inclusion of older, rebedded fossils, might explain some of the other distinctions mentioned above. It is also possible that the distinctions mean that a few of the Prince Patrick Island sites contain slightly older Beaufort sediments than the majority.

Some samples are separate from the others partly by absence of taxa seen in virtually all others. For example, FG-10a/2 (Figures 3F,5) at the Green Bay Section lacks *Abies, Pinus, Thuja, Epipremnum, Aracites*, and *Weigela* (Table 1). It also contains fossils of several plants not seen or at least rare in other samples (e.g. *Parnassia, Papaver*), unusually well preserved leaves of *Dryas*, and a few fossils of open-ground plants such as *Saxifraga oppositifolia* and *Oxyria*.

In Table 1 most of the plant fossils are only tentatively ("cf".) referred to extant species. Even those which are indistinguishable from their modern counterparts could represent extinct species. A few of the fossils, such as *Epipremnum, Paliurus, Myrica* and *Aracites* clearly represent extinct genera or species.

Fossils referred to *Epipremnum crassum* are now known to occur at a number of northern North American Neogene sites (Matthews and Ovenden, in preparation). They are not abundant or well preserved in any of the Prince Patrick Island samples, but the best are identical to well-preserved fossils of this kind from the lower part of the Ballast Brook exposure on northern Banks Island (fossils referred to *Menyanthes* by Hills (1975)). Although none of the *Epipremnum*-like fossils from the Beaufort Formation have been compared with type material, they match the description and illustrations provided by Reid and Reid (1915) for *Epipremnum crassum*, which Madison and Tiffney (1976) conclude is probably an extinct representative of the aroid subfamily Monsteroideae. Gregor and Bogner (1984) transferred *E. crassum* to the organ genus *Scindapsites*. The best preserved fossils from Prince Patrick Island also resemble illustrations and descriptions of seeds of the extant *Scindapsus officinalis* (Madison and Tiffney 1976). Both *Epipremnum* and *Scindapsus* are presently tropical to subtropical plants. The Beaufort Formation fossils show that the group of arums to which

they belong formerly had a wider ecological amplitude than it does today (Matthews 1987A). *Epipremnum crassum* ranges from Oligocene to late Pliocene (Madison and Tiffney 1976) with the latest records coming from the Netherlands (Reid and Reid 1915).

Aracites fruits(?) (referred to *Aracispermum* in Matthews 1987A) are thought to represent another extinct genus of arums (Nikitin 1957). The fossils from Prince Patrick Island are identical to those shown in Plate 9.1, Figures 3 and 4 of Matthews (1987A). They are also similar to fossils originally referred to *Hippuris globosa* by Reid and Reid (1915), but subsequently assigned to *Aracites* by Nikitin (1957). Such fossils are now known from a number of late Tertiary northern North American sites (Matthews and Ovenden, in preparation) and, the genus, if not the same species, survived until the early Quaternary in Europe and North America (Aalto and Hirvas 1987; Klassen *et al.* 1988). One occurrence in an autochthonous peat from Geodetic Hills, Axel Heiberg Island is of note because it indicates the type of site where this extinct plant once grew. The peat is dominated by the mosses *Drepanocladus aduncus*, *Calliergon richardsonii* and *Campylium stellatum/arcticum* (L. Ovenden, unpublished Geological Survey of Canada Fossil Bryophyte Report LO-27). *Ranunculus pedatifidus* was the most abundant vascular plant with other fossils representing *Ranunculus hyperboreus*, *R. lapponicus*, *Carex aquatilis* etc. (J.V. Matthews, Jr. unpublished Geological Survey of Canada Plant Macrofossil Report 89-09). So apparently *Aracites* was a plant of wet peaty depressions such as occur commonly today in the subarctic region.

Another distinctive plant fossil occurring in several Prince Patrick Island assemblages is tentatively referred to the genus *Paliurus*. In Figures 6b and 6c we show well-preserved specimens from two other late Tertiary sites. The Prince Patrick fossils are identical but not as well preserved. The true familial and generic placement of these fossils awaits further study. Nevertheless, despite size-differences, the distinctive trilocular, three-valved fruits are similar to those referred to *Paliurus* (Rhamnaceae) by other authors (Dorofeev 1963, 1972; van Der Burgh 1987). *Paliurus* fossils are now known to occur in a number of Neogene sites in northern North America, including the 5.7 million year Lava Camp locality in western Alaska (Matthews and Ovenden, in preparation). The northernmost record is from the Strathcona Fiord region of Ellesmere Island (Figure 1) (J.V. Matthews, Jr. unpublished Geological Survey of Canada Plant Macrofossil Report 88-25; Fyles 1989).

Several Prince Patrick Island samples contain poorly-preserved fruits of *Myrica* (Figure 6g). Most specimens lack the lateral scales which are typical of *Myrica gale* and

related species, but clearly belong to the subgenus *Gale*. Those retaining the lateral scales are more like the fossil species *M. eogale* (Nikitin 1976) from Siberia than to the extant *M. gale*. However, as with many of the other fossils discussed here, a definite conclusion must await comparison with type material. Fossils similar to *M. eogale* have also been found in the Kap København Formation of northern Greenland and the Beaufort Formation on Meighen Island (Bennike 1987; Matthews 1987A), and more recently from organic debris in high-level alluvium on Ellesmere Island (Fyles 1989; J.V. Matthews, Jr. unpublished Geological Survey of Canada Plant Macrofosill Report 88-24).

Bryophytes

Table 2 is a pooled list of bryophyte fossils from a number of Prince Patrick Island Sites. Two of the sites (HCA19-1c and Devaney Section 6a) contained detrital organic deposits that were of a finer facies than is typical of the Beaufort Formation. As expected of allochthonous assemblages, they contain species representing several different biotopes such as: (1) sedge-moss wetlands (*Cinclidium, Paludella squarrosa, Meesia triquetra, Catoscopium nigritum, Campylium stellatum/arcticum, Drepanocladus revolvens, Calliergon giganteum, Scorpidium scorpioides, and Tomenthypnum nitens)*; (2) drier, less organic soils (*Ditrichum flexicaule, Tortella fragillis, Rhacomitrium, Aulacomnium acuminatum, Timmia, Hypnum hamulosum, Hylocomium splendens)*; (3) stream margins (*Bryobrittonia, Philonotis, Cratoneuron filicinum, Amblystegium*); and (4) boreal forest (*Pleurozium, Sphagnum*).

In contract with the vascular plant fossils, none of the moss taxa is extinct, and moss species listed in Table 2 still occur in the Arctic today. As with the vascular plants, the epiphytic, acid-bog and forest-floor moss flora is seriously under-represented in the list. For example the feathermoss assemblage, so characteristic of modern boreal forest, is virtually absent except for rare fragments of *Pleurozium schreberi*. We attribute these deficiencies to over-representation of floodplain species, i.e. the same taphonomic bias thought to be responsible for the dominance of herbs among the vascular plants.

The other two samples listed in Table 2 were studied because they differed from typical Beaufort organic detritus by their more fibrous character, indicating that they might be autochthonous. One sample (FG11c2), from the thick fibrous peat horizon at the Green Bay Section (Figures 3(F), 5) displays horizontally-oriented moss stems forming 'felted' beds that cannot be clearly separated. It is dominated by *Drepanocladus* and *Calliergon*. Unlike

the detrital assemblages, all of the identified mosses now grow in one biotope: calcareous sedge-moss wetland. Many autochthonous Low-Arctic Holocene peats are also dominated by *Drepanocladus* and *Calliergon giganteum* (L. Ovenden, unpublished data from Victoria Island, N.W.T.).

The sample from Landing Lake (Figure 2), appeared in the field to come from a tabular fragment of a moss-dominated turf layer that had slumped en masse into the river, and been buried before being disaggregated. Similar fibrous mossy "clasts" are seen in alluvial sediments of modern braided-streams in the boreal zone. The Landing Lake sample contains mosses that might all have grown on calcareous floodplain sediments. Most grow today in damp or periodically wet sites fed by calcareous seepage, which can occur in floodplain depressions or along a stream margin (*Bryum pseudotrichetrum, Paludella squarrosa* (Figure 8), *Philonotis fontana, Campylium stellatum/arcticum, Cratoneuron filicinum*, and *Tomenthypnum*). Also present are a few species of: (1) well-drained sites *(Aulacomnium acuminatum, Drepanocladus uncinatus)*; (2) disturbed areas (*Ceratodon purpureus*;) and (3) alluvium *(Thuidium abietinum)* (Steere 1978). The assemblage lacks the characteristic mosses of peaty, sedge-moss wetlands and ponds *(Sphagnum, Calliergon, Scorpidium scorpioides*, and aquatic *Drepanocladus* spp.) which are common in the other three samples.

Insects

Virtually all of the Prince Patrick Island samples examined contain insect fragments. Their preservation is more like that seen on Meighen Island than in the Beaufort Formation at Ballast Brook on Banks Island. Only half as many taxa are known from Prince Patrick Island as from Meighen Island (Matthews 1977A), but this may be a sampling bias related to the larger volume of Meighen Island sediments examined for insects.

The most diverse Prince Patrick Island fossil arthropod assemblage - much richer than the pooled Devaney Section 1 assemblage - is sample FG-10a/2 of Green Bay (Figure 5). It contains at least 45 taxa. As with the vascular plant macrofossils, we suspect the high diversity is taphonomic in origin because FG-10a/2 detritus was much finer than other samples, permitting preservation of many fragile insect fossils.

In common with Beaufort samples from Meighen and Banks island (Matthews 1977A), most Prince Patrick Island insect fossils are from beetles (Coleoptera) (Table 3). The taxa in the list represent several different biotopes, but the majority are beetles that are either

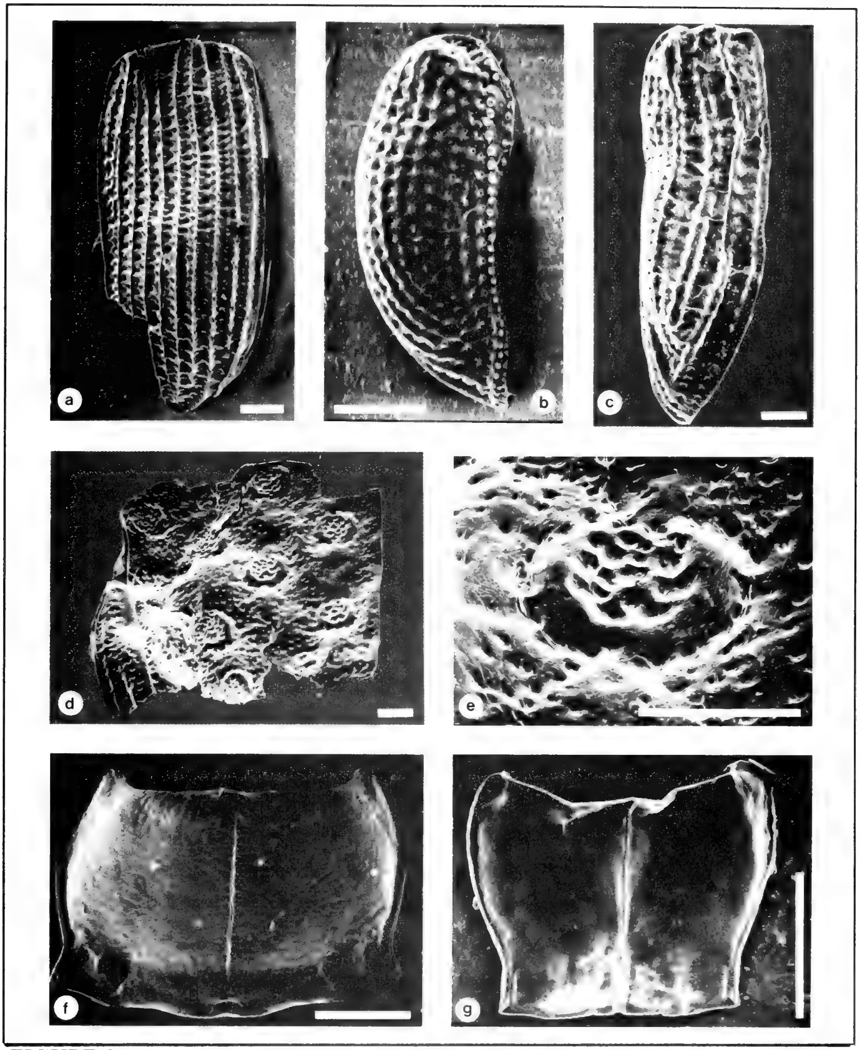


FIGURE 8: Scanning Electron Microscope images of insect fossils from the Beaufort Formation on Prince Patrick Island. Scale bar=0.3 mm. (a) GSC-95889: left elytron of a beetle: family and genus unknown, sample FG-87-1e. (b) GSC-95890: Georyssus sp., side view of right elytron, sample FG-87-1e. (c) GSC-85891: left elytron of a beetle: family and genus unknown, sample JDB-19e. This taxon is found in fossil assemblages from northern Banks Island, but has not been seen from Meighen Island. (d) GSC-95892: Elaphrus cf. E. clairvillei Kirby, fragment of left elytron, sample FG-87-18b. (e) enlargement of elytral fovae of specimen GSC-95892. (f) GSC-95893: Bembidion (Chrysobracteon) sp., pronotum, sample JDB-13b. (g) GSC-95894: Platidiolus cf. P. vandykei Kurn; pronotum, sample FG-87-10a/2.

typical of active floodplain sites near the river *(Bembidion sordidum, Bembidion (Chrysobracteon)* sp.: Figure 8f, *Nebria, Agonum bicolor, Aegialia, Morychus, Georyssus*: Figure 8b) or live in proximal wetland biotopes *(Simplocaria, Ochthebius, Helophorus, Gymnusa)*. Many of them can be found in Quaternary assemblages from the northern boreal zone. What sets Beaufort Formation assemblages apart from Quaternary samples is the presence of a few fossils of extinct species and others, such as all Pselaphidae and *Georyssus*, that now live well south of northern Canada.

DISCUSSION

Age of the Beaufort Formation on Prince Patrick Island

It is difficult to determine the age of the Beaufort Formation. It is interbedded with fossiliferous marine sediments at only one locality, Meighen Island, and to date has not yielded the types of terrestrial fossils, such as vertebrates, which ordinarily allow reference to a world-wide chronostratigraphic framework. Matthews (1977A, 1977B) has attempted to compare Beaufort insect assemblages with those from sites of known age, such as Lava Camp in western Alaska, but could suggest only that the Beaufort Formation on Meighen Island was younger than 5.7 million years old. Amino-acid ratios on mollusc shells from the Meighen Island marine unit have been interpreted to mean that associated terrestrial sediments were deposited only shortly before onset of nearly continuous cold climate (Brigham-Grette *et al.* 1987), which would mean an age no older than mid-Pliocene. Foraminiferal data (D.H. McNeil, unpublished Geological Survey of Canada Paleontology report 5) 1988) and new Sr-isotope dates in the 3 million year range (personnal communication to J.G.F. from K. Miller, 1989) show (contrary to the opinion expressed in Matthews 1989) that the Meighen Island sediments are no older than early Pliocene.

Although the above conclusions deal with Meighen Island, here we are primarily concerned with the age of the Beaufort Formation on Prince Patrick Island. The only available means of estimating that age is by comparison of plant assemblages with those from Meighen Island, other Beaufort sites and dated floras from Cook Inlet, Alaska.

Table 4, at the end of this paper, summarizes floristic data from various Beaufort localities on southern and northern Banks Island, Prince Patrick Island, Meighen Island and the 2 million year old Kap København deposits in northern Greenland (Matthews 1987A;

Bennike, in press). While it is at best a provisional template, which will undoubtedly be greatly modified as fossils from other newly discovered localities become available, the table does provide potential chronological information. For example, Prince Patrick Island macrofloras appear similar both to those from the "upper Beaufort" at Ballast Brook and Meighen Island. The similarity to Meighen Island becomes even more apparent if taxa encountered rarely at only a few of the Prince Patrick sites (see above) are removed from consideration. Remaining differences, such as the presence of seeds of *Paliurus* and *Decodon* at some Prince Patrick Island sites and not at Meighen Island might, as Hills (1975) suggested, be due to the latitudinal gradient of the time. He proposes that Prince Patrick and Meighen island floras are about the same late Miocene age (Homerian of Wolfe 1981). If they are the same age, then new data from Meighen Island (superseding information presented in Matthews 1989) showing the marine unit there was deposited about 3 million years ago, means that the Prince Patrick Island deposits discussed here may be just as young (early Late Pliocene (Clamgulchian)) rather than late Miocene.

It is highly unlikely that Prince Patrick Island deposits could be younger than those on Meighen Island, but we cannot rule out the possibility that they are older, and that the distinctions exhibited in Table 4 have both a chronological and a geographical basis. As indicated earlier, Hills (1975) reports a fossil nut of *Carya* from the island, which suggests the presence of sediments older than those discussed here, but until that single occurrence is better documented, it remains at most an intriguing curiosity.

Taphonomy

All of the macrofossils of higher plants discussed here were stream-transported before being deposited, so differential sorting and preservation have biased the assemblages (Spicer 1980, Spicer and Wolfe 1987) making it difficult to read paleoenvironmental information from them. As might be expected of fossils from alluvial detritus, many of the plants listed in Table 1 are typical of floodplain or poorly-drained spots nearby. Some in the latter class (e.g. *Menyanthes* and *Potamogeton*) produce tough seeds or fruits that float well and are easily moved by streams and deposited with alluvial sand and silt.

The unique and diverse insect and plant assemblage from sample FG-10a/2 at Green Bay (Figures 1,5) is probably the result of taphonomic bias, though the absence of key taxa seen at virtually all other sites is difficult to explain thus. Spicer (1980) has shown that

organic deposits dominated by fine, well-preserved plant detritus, like FG-10a/2, are typical of certain parts of alluvial depositional systems.

Rebedding of older fossils is a special type of taphonomic bias - one which may also severely hinder the interpretation of fossil floras (Matthews *et al.* 1986; Dyke and Matthews 1987). Many samples discussed here contain fragments of amber and the distinctive needles of *Sciadopitys*, the Japanese Umbrella Pine. Both are probably derived from the Paleogene Eureka Sound Group. Could there be other less obvious rebedded fossils of late Tertiary age contaminating Prince Patrick assemblages? Fossils of the *Betula apoda* type, *Microdiptera* and *Cleome* were rare and rather poorly preserved in the Prince Patrick Island assemblages. Perhaps they are rebedded from an older unit no longer exposed on the island, and the same explanation may apply to the *Carya* fossil reported by Hills (1975).

There is no foolproof method of assessing the magnitude of the rebedded-fossil problem. All we can say is that most samples discussed here contained fossils that are similiarly preserved, hence they are assumed to be approximately contemporaneous.

Climate of Prince Patrick Island during Beaufort Time

Figure 7 shows the present distribution of some taxa to which Prince Patrick Island fossils are referred. Because many fossils probably represent extinct species, they should not be used for inferring paleoclimate (Wolfe and Tanai 1980). Comparisons based on vegetation rather than flora are a more reliable climatic indicator. For the time being, the best indication of climate on Prince Patrick Island during deposition of Beaufort sediments is the location of the region with respect to regional treeline.

Today western Prince Patrick Island, has a mean July temperature below 4°C, and is beyond the limit of woody plants (Edlund 1986; this volume). Along with Meighen Island and some of the other western QEI, it lies within the most severe climatic region in the Canadian Arctic Archipelago (Maxwell 1981). Contemporary treeline corresponds approximately with the 13°C mean July isotherm; so a forested Prince Patrick Island would have had a mean July temperature at least 9°C warmer than now.

The moss floras of North American boreal and arctic regions are much more alike than the vascular plant floras of these bioclimatic zones, making it difficult to interpret paleoclimate from a fossil assemblage of northern mosses strictly on the basis of their modern distributional limits. Nevertheless, three of the four moss assemblages in this study

include species which are now extinct or very rare on the Arctic Islands (Table 1). In this group are all *Sphagnum* spp., *Diacranum leioneuron*, *Paldudella squarrosa*, *Amblystegium tenax*, and *Pleurozium schreberi* (Ireland *et al.* 1987). Most of these species occur as rare fragments in the two Beaufort detrital samples. *Paludella squarrosa* (Figure 9) is a major element of the sample from Landing Lake. Taken together, these 'boreal' mosses indicate a paleoclimate at least as warm as that of the Low-Arctic zone today.

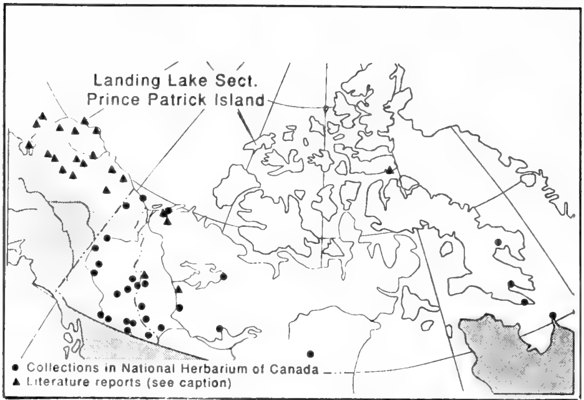


FIGURE 9: Distribution of the moss Paludella squarrosa in the Northwest Territories, Yukon Territory and Alaska north of the Arctic Circle (66°30'N). Literature records (triangles) from Steere (1978); Bird et al. (1977); Holman and Scotter (1971); and Brassard (1971).

Paleobiogeography

In late Tertiary time Asia and North America were joined by an isthmus, and the Arctic Islands were much more a single land mass than they are now (Craig and Fyles 1960, 1965). There was ample opportunity for biotic exchange between Asia and North America - the more so because cold climate did not then impose the severe dispersal filter that it did during exposure of the Bering Isthmus in Quaternary time. Thus it is not surprising that many of the vascular plant taxa in the Prince Patrick Island assemblages appear similar to species described from east Asian and European floras (Dorofeev 1963; Nikitin 1976; Reid and Reid 1915).

The moss assemblages (Table 2) include species which belong to the circumpolar element of the Arctic moss flora. These species occur throughout the Arctic and in a few northern mountain ranges, but unlike the vascular plants, do not extend into northern hemisphere boreal and temperate zones. Steere (1965 1976) has listed species with this pattern, inferring that they are a remnant of a widespread, temperate Tertiary flora, isolated from their nearest relatives by Pleistocene glaciations. *Bryobrittonia longipes, Aulacomnium*

acuminatum, *Cinclidium arcticum*, and *C. latifolium* are members of the circumpolar arctic element. Their occurrence in Tertiary fossil assemblages of distinctly boreal character from Prince Patrick Island is significant support for this phytogeographic theory.

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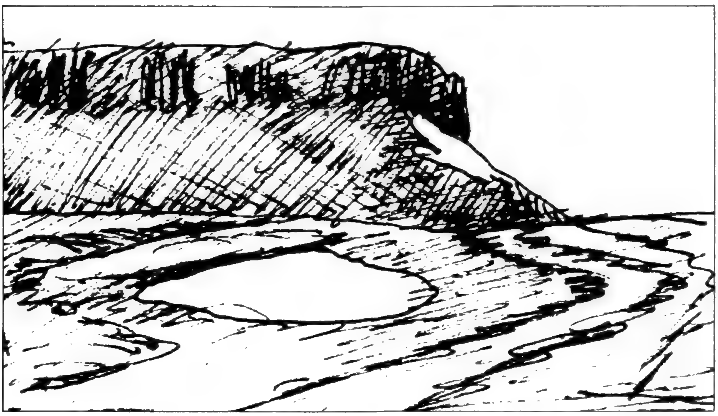

Illustrated by Brenda Carter

TABLE 1: PLANT MACROFOSSILS FROM SELECTED SITES ON PRINCE PATRICK ISLAND.

	[b]FG18	[c]Devaney Sect. 1							[c]Green Bay		Landing Lk.
		6a	9	2	13&1e	11	14	2a	10a/2	11c6	
Amber	+	+			+	+		+	+	+	+
MYCOPHYTA											
Actinorhizal nodules	+	+	+								
PHYCOPHYTA											
Characeae											
Chara/Nitella								+	+		
BRYOPHYTA		+	+		+	+	+	+	+	+**	+**
PTERIDOPHYTA											
Selaginellaceae											
Selaginella sp.				+		+	+		+		
SPERMATOPHYTA											
Pinaceae											
Abies sp.	+			+	+	+	+	+			+
Larix sp.	+		+	+	+	+	+	+	+		+
Pinus sp.	+		+		+	+		+			+
Pinus strobus type			+								
Picea sp.	+				+	+	+		+	+	+
Taxodiaceae											
Metasequoia sp.†	+										
Cupressaceae											
Thuja occidentalis L.	cf.		cf.	cf.				cf.			
Sparganiaceae											
• *Sparganium* sp.	+	+							+		
• *S. hyperboreum* Laest.							+				
Potamogetonaceae											
• *Potamogeton* spp.	+		+	+	+		+		+		+
Alismaceae											
• *Sagittaria* sp.	?	+			?						+
Gramineae											
Genus sp.					+			+	+		
• *Glyceria* sp.	?										
Cyperaceae											
Carex spp.	+	+		+	+	+		+	+	+	+
• *C.* sect. *acutae*			+								
• *Eleocharis* sp	+				+		?				
• *E. palustris/uniglumis* type								+			
• *Rhynchospora capitellata* (Michx.)Vahl.									+		
• *Scirpus* sp..			+	+	+		+	?	+		
• *S. validus* type									+		
Araceae											
Epipremnum crassum Reid&Reid††		+	+	+			+				
Aracites sp.	+		+	+	+		+				
Juncaceae											
• *Juncus* spp.									+		
• *Luzula* sp.							?				
Salicaceae											
Populus sp.					+						
• *Salix* sp.	+		+	+	+				+		+
Myricaceae											
Myrica eogale Nikit.††	cf.	?	?	cf.	cf.		cf.		cf.		
Comptonia sp.		+									?

TABLE 1: (cont.)

	[b]FG18	[c]Devaney Sect. 1							[c]Green Bay		Landing Lk.
		6a	9	2	13&1e	11	14	2a	10a/2	11c6	
Betulaceae											
Alnus sp.			+		+				+		+
A. crispa (Ait.)Pursh	+	+	+						+		
• *A. incana* (L.)Moench	+		+	+		+			+		+
Betula dwarf shrub	+				+			+	+	+	
Betula arboreal type	+			+	+	+			+		+
Betula apoda Nikit.††	cf.										?
Tubela sp.††	cf.										
Polygonaceae											
Oxyria digyna (L.)Hill	+			+			+	+	+		
• *Polygonum* sp.			+								
• *Rumex* sp.	+		+	+	+	+	+	+	+		?
Chenopodiaceae											
• *Chenopodium* sp	+		+		+	+			+		
Portulacaceae											
Claytonia sp.									+		
Caryophyllaceae											
Genus?			+								
Melandrium sp									+		
Silene sp									+		
Nymphaeaceae											
• *Nuphar* sp.		+			+						
Ranunculaceae											
Ranunculus sp.					+			+	+		
• *R. hyperboreus* Rottb.		cf.	cf.			cf.		cf.			cf.
• *R. sceleratus* type				?							
R. pensylvanicus L.f.	cf.										
R. lapponicus L.		cf.							cf.	+	cf.
Thalictrum sp.	+				+			+			+
Papaveraceae											
Papaver sp.								+	+		
Capparidaceae											
Cleome sp.			+								+
Cruciferae											
• *Rorippa* sp.								+	+		
Draba sp.									+		
Saxifragaceae											
• *Parnassia* sp.									+		
Saxifraga sp.											?
S. oppositifolia L.									+		
Rosaceae											
Dryas sp.					+		?	+			+
Physocarpus sp.	+		+	+	+						+
Potentilla sp.				+		+	+	+	+	+	
• *P. palustris* (L.)Scop.	cf.						cf.				
P. norvegica L.	cf.	cf.		cf.					cf.		
• *P. anserina* L.									cf.		
Prunus sp.	+		+		+						
P. Maximoviczii Ruprecht.				cf.							
Rubus ideaus L.	cf.								cf.		
Rubus sp.		+	+			+					
Fragaria									cf.		
Rhamnaceae											
Paliurus sp.		+	+								+
Hypericaceae											
• *Hypericum* sp.	+					+		+	+		
Violaceae .											
Viola sp.	+	+		+					+		
Lythraceae											
• *Decodon* sp.	+	+	+	+	+	+	+	+	+		+
Microdiptera sp.††											+

TABLE 1: (cont.)

	[b]FG18	[c]Devaney Sect. 1 6a	9	2	13&1e	11	14	2a	[c]Green Bay 10a/2	11c6	Landing Lk.
Haloragaceae											
• *Hippuris* sp.	+	+	+	+	+		+	+	+		+
• *Myriophyllum* sp.											
• *M. exalbescens* Fern.								cf.			
Araliaceae											
Aralia sp.											+
Umbelliferae											
Genus?									+		
Ericaceae											
Vaccinium vitis-idaea L.										cf.	
Empetrum sp.			+	+			+		+		
Andromeda sp.	+	+	+	+		+			+		
Vaccinium sp.						+				+	
Chamaedaphne sp.	+		+		+	+			+		
Cornaceae											
Cornus sp.		+									
• *C. stolonifera* Michx.	cf.			cf.	cf.						cf.
Primulaceae											
Primula sp.									?		
Gentianaceae											
• *Menyanthes trifoliata* L.	+	+	+	+	+			+	+	+	
Menyanthes (<2mm)††	+	+			+					+	
Verbenaceae											
• *Verbena* sp.	+		+			+		+	+		
Labiatae											
• *Lycopus* sp.				+	+				+		
• *Teucrium* sp.			+								
Caprifoliaceae											
Sambucus sp.	+	+			+	+	+				+
Weigela sp.†				+	+	+					
Compositae undet.								+			

[a] For location of sites see Figure 2. Stratigraphic position of samples from Devaney Sect. 1 and the Green Bay Section are shown in Figures 4 and 5 respectively.

b. FG18 = Site FG87-18 (Fig. 2) and pooled samples FG87-18 a,b abd c from the top middle and bottom on one 1m silt horizon.

[c] Only numbers are given for column heading, i.e., 9= JDB9, 1e=FG1e etc. Plants from samples FG1e and JDB13 are pooled because they both represent about the same stratigraphic horizon.

[d] Landing Lake = Devaney Section 8. The list is a combination of taxa in two samples: JDB46 and FG87-31a.

• indicates those taxa that now grow on floodplains or occur neaby and are readily incorporated into alluvial sediments.

•• indicates samples from which Bryophytes have been examined by Ovenden (this paper)

† = Extinct in North America

††= Extinct throughout the world

TABLE 2: BRYOPHYTE TAXA FROM THE BEAUFORT FORMATION AND RELATED UNITS ON PRINCE PATRICK ISLAND..

	Beaufort Detrital Samples[1]	Landing Lake	Green Bay (FG11c2)
Sphagnaceae			
Sphagnum sect. *Sphagnum*	+		
S. teres (Schimp.)Aongstr. ex C.Hartm.	+		
S. sect. *Subsecunda*	+		
S. sect. *Acutifolia*	+		
Ditrichaceae			
Ditrichum flexicaule (Schwaegr.)Hampe	+		
Distichoum capillaceum (Hedw.)B.S.G.	+	+	
Ceratodon purpureus (Hedw.)Brid.		+	
Dicranaceae	+		
Dicranum sp.			+
Encalyptaceae			
Bryobrittonia longipes (Mitt.)Horton	+		
Pottiacaea			
Tortella fragillis(Drumm.)Limpr.	+		
Grimmiaceae			
Rhacomitrium sp.	+		
Schistidium apocarpum ?	cf.		
Bryaceae			
Pohlia sp.	+		
Bryum spp.	+	+	+
Mniaceae			
Mnium marginatum(With.)Brid. ex P. Beauv.	cf.		
Cinclidium arcticum(B.S.G.)Schimp.	+		
Cinclidium latifolium Lindb.	+	+	cf.
Cinclidium sp		+	
Aulacomniaceae			
Aulacomnium palustre(Hedw.)Schwaegr.	+		
A. acuminatum(Lindb.&H.Arnell)Kindb.	+	+	
A. turgidum(Wahlenb.)Schwaegr			+
Meesiaceae			
Paludella squarrosa(Hedw.)Brid.	+	+	
Meesia triquetra(Richt.)Aongstr.	+	+	+
M. longiseta Hedw	+	+	
Bartramiaceae			
Philonotis fontana (Hedw.)Brid.	+	+	
Timmiaceae			
Timmia sp.	+	+	
Thuidiaceae			
Thuidium abietinum (Hedw.)B.S.G.		+	

TABLE 2: (cont.)

	HCA19-1c & Devaney 6a	Landing Lake	Green Bay (FG11c2)
Amblystegiaceae			
Cratoneuron filicinum (Hedw.)Spruce	+	+	
Amblystegium riparium (Hedw.)B.S.G.	cf.		
A. tenax (Hedw.)C.Jens.	cf.		
Campylium stellatum/arcticum (Williams)Broth.	+	+	+
C. polygonum (B.S.G.)C.Jens.	+		
Drepanocladus revolvens (SW.)Warnst.	+		
D. exannulatus (B.S.G.)Warnst.	+		
D. fluitans (Hedw.)Warnst.	+		
D. pseudostramineus (C.Müll.)Roth	+		
D. tundrae (H.Arnell)Loeske	+		
D. aduncus (Hedw.)Warnst.	+		+
D. uncinatus (Hedw.)Warnst.	+	+	
Calliergon giganteum (Schimp.)Kindb.	+		+
Scorpidium scorpioides (Hedw.)Limpr.	+		+
Brachytheciaceae			
Tomenthypnum nitens (Hedw.)Loeske	+	+	
Brachythecium turgidum (C.J. Hartm.)Kindb..	cf.		
Hypnaceae			
Orthothecium chryseum (Schwaegr. ex Schultes)B.S.G.			+
Hypnum hamulosum B.S.G.	+		
Hypnum sp.	+		
Hylocomiaceae			
Pleurozium schreberi (Brid.)Mitt.	+		
Hylocomium splendens (Hedw.)B.S.G.	+		
Polytrichaceae			
Polytrichum alpinum Hedw.	cf.		

1. Samples include FG-1e, FG-2a, HCA19-1c and FG-17d (from Devaney Sect. 6a)

TABLE 3: PRELIMINARY LIST OF INSECT AND OTHER ANIMAL FOSSILS FROM THE BEAUFORT FORMATION, PRINCE PATRICK ISLAND..

	aFG18	bDevaney Section 1	cGreenBay FG10a/2
PORIFERA			
Haplosclerina			
Spongillidae			
Spongilla type			+
BRYOZOA			
Cristatella mucedo L.	+	+	
ARTHROPODA			
INSECTA			
Odonata		+	
Homoptera			
Cicadellidae			
Genus?	+		+
Coleoptera			
Carabidae			
• *Trachypachus* sp.	+	+	
Carabus sp.		+	
Carabus (*Hemicarabus*) sp.	+		
• *Nebria* sp.	+	+	
• *Notiophilus* sp.	+	+	
Diacheila polita Fald.	cf.	cf.	
Diacheila sp.	+	+	
Blethisa multipunctata L.		cf.	
Elaphrus clairvillei Kby.	cf.		
• *Elaphrus* sp.		+	+
Loricera sp.		+	
Dyschirius sp.	+	+	+
D. tridentatus grp.		+	
• *Platidiolus vandykei* Kurn.			cf.
Trechus sp.		+	
• *Asaphidion yukonense* Wick.			cf.
• *Asaphidion alaskanum* Wick.	cf.	cf.	
• *Bembidion* (*Chrysobracteon*) sp.	+	+	
• *Bembidion dyschirinum* LeC.		cf.	
Bembidion quadrimaculatum L.			cf.
• *Bembidion sordidum* Kby.			+
Bembidion(*Trepanedoris*) sp.			+
Pterostichus sp.	+		
Pterostichus(*Cryobius*) spp.	+	+	
Pterostichus vermiculosus Men.	cf.	cf.	
• *Agonum bicolor* Dej.		cf.	
Amara sp.		+	
Amara (*Curtinotus*) sp.	+		
Dytiscidae			
Genus?	+	+	
Hygrotus sp.		+	
Colymbetes sp.			+
Hydrophilidae			
Helophorus sp.	+	+	+
Helophorus (*Cyphelophorus*) sp.			+

TABLE 3: (cont.)

		FG18	Devaney Section 1	Green Bay FG10a/2
	Hydraenidae			
	Ochthebius sp.			+
	Georyssidae			
•	*Georyssus* sp.		+	
	Staphylinidae			
	Micropeplus sculptus LeC.		+	
	Micropeplus cribratus LeC.		+	
	Kalissus nitidus LeC.		cf.	
•	*Bledius* sp.	+	+	+
	Olophrum sp.			+
	Acidota sp.		+	
	Micralymma type			+
	Stenus sp.	+	+	+
	Tachinus sp.		+	+
	Aleocharinae	+		+
	Gymnusa sp.	+		+
	Pselaphidae			
	Genus?			+
	Silphidae			
	Silpha sp.	+	+	
	Scarabaeidae			
•	*Aegialia* sp.	+	+	+
	Byrrhidae			
	Curimopsis sp.	+		
	Simplocaria sp	+	+	+
•	*Morychus* sp.		+	+
	Cytilus alternatus type		+	+
	Heteroceridae			
	Heterocerus sp.	+		
	Elateridae			
	Genus?			+
	Anobiidae			
	Genus?			+
	Coccinellidae			
	Genus?			+
	Nephus sp.			+
	Lathridiidae			
	Genus?	+		+
	Chrysomelidae			
	Donaciinae	+	+	+
	Chrysomela sp.			+
	Curculionidae			
	Phyllobius sp.		?	
	Vitavitus sp.	+		+
	Lepyrus sp.	+		
•	*Lepidophorus* sp.	?		
	Notaris sp.		?	
	Pissodes sp.		+	
•	*Grypidius* sp.		+	
	Scolytidae			
	Several genera			

TABLE 3: (cont.)

	FG18	Devaney Section 1	Green Bay FG10a/2
Diptera			
Tipulidae			
Tipula sp.			+
Chironomidae			
Genus?			+
Xylophagidae			
Xylophagus sp.	+		+
Hymenoptera			
Symphyta			+
Ichneumonoidea			+
Diapriidae		+	
Formicidae	+		
CRUSTACEA			
Daphnia sp.			+
ARACHNIDA			
Acari			
Oribatei	+	+	
Cepheus type			+

a. FG18 = Site FG87-18 (Fig. 2) and pooled samples FG87-18 a,b abd c from the top middle and bottom on one 1m silt horizon.
b. Devaney Sect. 1= all fossils identified to date from the numerous samples from this section. Sample FG87-1e (Fig. 4) was one that had an abundance of insect fossils.
c. Green Bay, FG10a/2=Green Bay section, lowest Beaufort sample (see Fig. 5).
* Identifies taxa which are most often collected in stream-side communities.

TABLE 4: COMPARISON OF DISTRIBUTION WITHIN BEAUFORT FORMATION AND AT KAP KØBENHAVN (GREENLAND) OF SELECTED PLANT TAXA[a].

Taxon	Banks Is DHB	Banks Is L	Banks Is U	Prince Pat.Is.	Meighen Is.	K.København Greenland
Phyllanthus sp.	+					
Actinidia sp.†	+					
Liriodendron sp.	+					
Metasequoia sp.†	+					
Tsuga sp.	+					
Taxodium sp.	+					
Glyptostrobus sp.†	?	+				
Cleome sp.†	+		+	+*		
Betula apoda type†	+		+	+*		
Epipremnum crassum †	+	+	+	+		
Microdiptera sp.†	+		+	+*		
Weigela sp.†	+			+		
Paliurus sp.	+			+		
Decodon sp.	+		+	+		
Abies sp.	+[b]		?	+		
Verbena sp.			?	+		
Comptonia sp.†	+		+	+	+	
Pinus (5-needle type)	+	+	+	+	+	
Myrica eogale type†		+	+	+	+	+
Picea sp.	+	+	+	+	+	+
Larix sp.	+	+	+	+	+	+
Thuja occidentalis	cf.			+	+	+
Oxyria digyna				+	+	+
Menyanthes trifoliata		+	+	+	+	+
Betula dwarf shrub type			+	+	+	+
Saxifraga oppositifolia					+	
Viburnum edule						+

a. **Banks Island**-L. = lower Beaufort Formation at Ballast Brook; **Banks Island-DHB**=Beaufort Formation at Duck Hawk Bluffs (Matthews, 1989); **Banks Island-U**=Upper Beaufort Formation at Ballast Brook; **Prince Pat.**=Pooled Prince Patrick Beaufort localities; **Meighen Is.**=pooled samples from several sites on Meighen Island (Matthews, 1987a); **K.København, Greenland**=Kap København site, northern Greenland (from Bennike and Böcher, in press and pers. comm., 1988).

b. *Abies* fossils from Duck Hawk Bluffs represent a species near *A. grandis*, while those from Prince Patrick Island refer to another species.

* indicates taxa which occur rarely in only a few Prince Patrick samples.

ICE AGE VERTEBRATES IN THE CANADIAN ARCTIC ISLANDS

C.R. Harington[1]

Abstract: Remains of Pleistocene (about 2 million to 10,000 years ago) vertebrates are rarely found in the Canadian Arctic Islands. From earliest to latest they include: a few fossils of middle Pleistocene interglacial (perhaps 700,000 years old) tundra-adapted animals from southern Banks Island; small seal, large whale, small horse and bison from last interglacial (or earlier) deposits near the Beaufort Sea coast; a mammoth and tundra muskox of possible early Wisconsin age from Garry Island in the same region; a middle Wisconsin Dovekie from southern Ellesmere Island and a tundra muskox of that age (or older) from Banks Island; as well as several species (e.g. mammoth, small horse, saiga antelope and tundra muskox) from late Wisconsin deposits of the western islands (Melville, Banks, Baillie and Herschel).

Early Holocene (about 10,000 to 5,000 years ago) vertebrates from the Arctic Islands are more commonly found and include: Oldsquaw duck, ringed seal, walrus, narwhal, bowhead whale, Peary caribou and tundra muskox. Many Holocene mammal (mainly marine mammal) remains have been collected from raised beaches in the archipelago during the past decade. Radiocarbon dates on these specimens indicate relatively warm (open water) conditions about 9,000 and 4,000 years ago.

Résumé: Les vestiges de vertébrés du Pléistocène (il y a environ 2 millions à 10,000 ans) ne se retrouvent que rarement dans les îles de l'Arctique canadien. Ils comprennent les vestiges de: quelques animaux fossiles adaptés à la toundra, dans le sud de l'île Banks, datant de l'époque interglaciaire du Pléistocène moyen, (il y a probablement 700,000 ans); grosse baleine, petit phoque, petit cheval et petit bison près de la côte de la mer de Beaufort, datant du dernier interglaciaire (ou plus récent); mammouth dans l'île Garry dans la même région, possiblement de la période inférieure du Wisconsinien; mergule nain dans le sud de l'île Ellesmere, datant du Wisconsinien moyen, et boeuf musqué de la toundra de l'île Banks, du même âge ou plus vieux; également plusieurs espèces datant du Wisconsinien supérieur, par exemple, mammouth, petit cheval, antilope saïga et boeuf musqué de la toundra.

Les espèces retrouvées dans les îles de l'Arctique canadien datant de l'Holocène inférieur comprennent: le canard kakawi, le phoque annelé, le morse, le narval, la baleine boréale (en grand nombre), le caribou de Peary et le boeuf musqué de la toundra. Des vestiges de plus en plus nombreux de mammifères, surtout marins, datant de l'Holocène, découverts sur les plages surélevées de l'archipel permettent de croire à un repeuplement accéléré des endroits couverts de glace lors de la dernière glaciation.

INTRODUCTION

This paper focuses mainly on vertebrates other than marine mammals, and on Pleistocene and early Holocene finds (Figure 1). Data on specimens (Table 1, at the end of this paper) usually include: identification, skeletal part, catalogue number, locality, collector(s), year of collection, radiocarbon dates, pertinent stratigraphy and references. Many of the specimens are in the Quaternary Zoology Collection of the National Museum of Natural Sciences (NMC) in Ottawa.

Of nearly 60 specimens dealt with, about a third are from Herschel Island in the Yukon Territory which, with islands near the mouth of the Mackenzie Delta and Baillie Islands, I consider to be part of the Canadian Arctic Islands. Specimens include approximately 17 genera, at least three of which represent birds.

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The earliest finds were made by members of expeditions exploring the islands (e.g. Nares' Royal Navy expedition to northern Ellesmere Island (1875-1876) (Figure 2), and the Canadian Arctic Expedition (1913-1918)). However, most finds have been made during the last 30 years by Quaternary geologists during the course of extensive field programs. Generally, sites have not proved sufficiently productive to warrant excavation by paleontologists. Nevertheless, it seems advisable to look carefully at the possibility of recovering Pleistocene vertebrate remains in the western Arctic Islands - particularly Banks and Herschel islands.

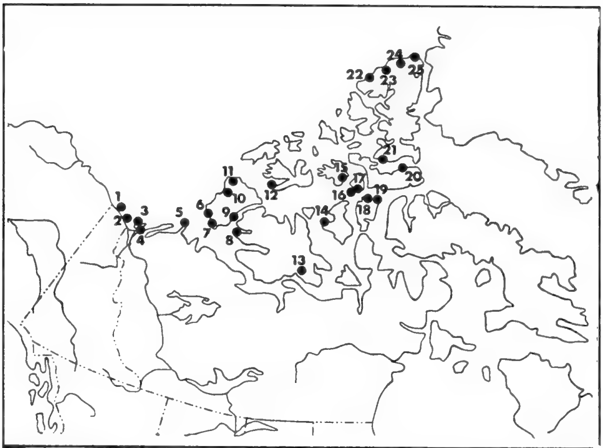

FIGURE 1: Some Quaternary vertebrate localities in the Canadian Arctic Islands that are mentioned in the text. Key: 1. Herschel Island, Y.T. 2. Mackenzie Bay ("Immerk") 3. Garry Island 4. Richards and Summer islands 5. Baillie Islands 6. Duck Hawk Bluff, Banks Island 7. Masik River, Banks Island 8. Cape Wollaston, Victoria Island 9. Jesse Bay, Banks Island 10. Bernard River, Banks Island 11. Ballast Brook, Banks Island 12. Cape James Ross, Melville Island 13. Ferguson Lake, Victoria Island 14. Cape Richard Collinson, Prince of Wales Island 15. Goodsir Inlet - Muskox River area, Bathurst Island 16. Griffith Island 17. Resolute area, Cornwallis Island 18. Cunningham River, Somerset Island 19. Northeast coast, Somerset Island 20. Truelove Inlet, Devon Island 21. Cape Storm, Ellesmere Island 22. Cape Woods, Ellesmere Island 23. Thores River, Ellesmere Island 24. Clements Markham Inlet - Piper Pass area, Ellesmere Island 25. Alert, Ellesmere Island.

PLEISTOCENE VERTEBRATES

The earliest reports involve lemming (*Dicrostonyx torquatus*) and ptarmigan (?*Lagopus* sp.), as well as an unidentified medium-sized mammal from interglacial deposits perhaps 700,000 years old on southern Banks Island. Paleoenvironmental data from deposits at Jesse Bay suggest a tundra-like landscape that was warmer than present (Miller 1985).

Remains of small seal (*Phoca* sp.), a large whale like the bowhead (cf. *Balaena mysticetus*), small horse (*Equus lambei*) and bison (*Bison* sp.) were derived from last interglacial (or earlier) deposits on or near islands off the Beaufort Sea coast (e.g. Herschel,

FIGURE 2: Bottom view of the basioccipital region of a tundra muskox (Ovibos moschatus; BM(NH) M3719) skull. Collected by members of the Nares Expedition from raised beach deposits near Alert, Ellesmere Island.

Summer and Richard's islands, as well as "Immerk" in Mackenzie Bay). J.S. Vincent (personal communication, 1985) considers that fragments of mammoth (*Mammuthus* sp.) and tundra muskox (cf. *Ovibos moschatus*) from Garry Island are probably of early Wisconsin age.

Bones of a small sea bird, the Dovekie (*Alle alle*), have been found in middle Wisconsin (about 40,000 years ago) deposits at Cape Storm on southern Ellesmere Island (Blake 1980). This was the first recorded evidence of a Pleistocene bird from the Canadian High Arctic; and the presence of an immature individual may mark the place as a former breeding colony. Until a recent report of two nesting sites at Home Bay, Baffin Island, no Dovekie breeding colonies were known in the Canadian Arctic (Finley and Evans 1984). Marine shells from the fossil-bearing deposit indicate a shallow marine environment with subfrigid to cold-temperate conditions in this ice-free enclave.

Possibly tundra muskoxen (*Ovibos moschatus*) survived the Wisconsin glaciation in a western Banks Island refugium, for remains from Bernard and Masik river areas have been radiocarbon dated at >34,000 yr B.P. and about 11,000 yr B.P. respectively (Maher 1968; Harington 1978).

Apparently several species of land mammals lived in the archipelago during the late Wisconsin, in addition to the muskox mentioned above. They include: mammoth (*Mammuthus* sp.; Figure 3) from Melville Island (about 22,000 yr B.P.), and possibly another one of this age or earlier from northern Banks Island (personal communication, L.V. Hills, 1977); small horse (*Equus lambei*) from Herschel Island (about 16,000 yr B.P.); and saiga antelope (*Saiga tatarica*) from Baillie Islands (about 15,000 yr B.P.). The Melville Island mammoth tusk deserves further comment. It is the most northerly record of a mammoth in North America. It is difficult to explain the presence of mammoths in this rather isolated region near the peak of the last glaciation, but it should be noted that much of the island seems to have been deglaciated before 18,000 years ago (Dyke and Prest 1986). Of great interest paleoclimatically is the saiga skull fragment from Baillie Islands (Figure 4). Presumably it, with mammoth, small horse and some bison fossils from that locality, is indicative of steppe-like grasslands along the arctic coast or northwestern North America during the late Wisconsin (Harington 1981). Other specimens of late Pleistocene (late Wisconsin?) age from Herschel Island include: woolly mammoth (*Mammuthus primigenius*); small horse (*Equus lambei*); large-horned bison (*Bison priscus*); helmeted muskox (cf. *Symbos cavifrons*); and tundra muskox (*Ovibos moschatus*) (Harington 1989).

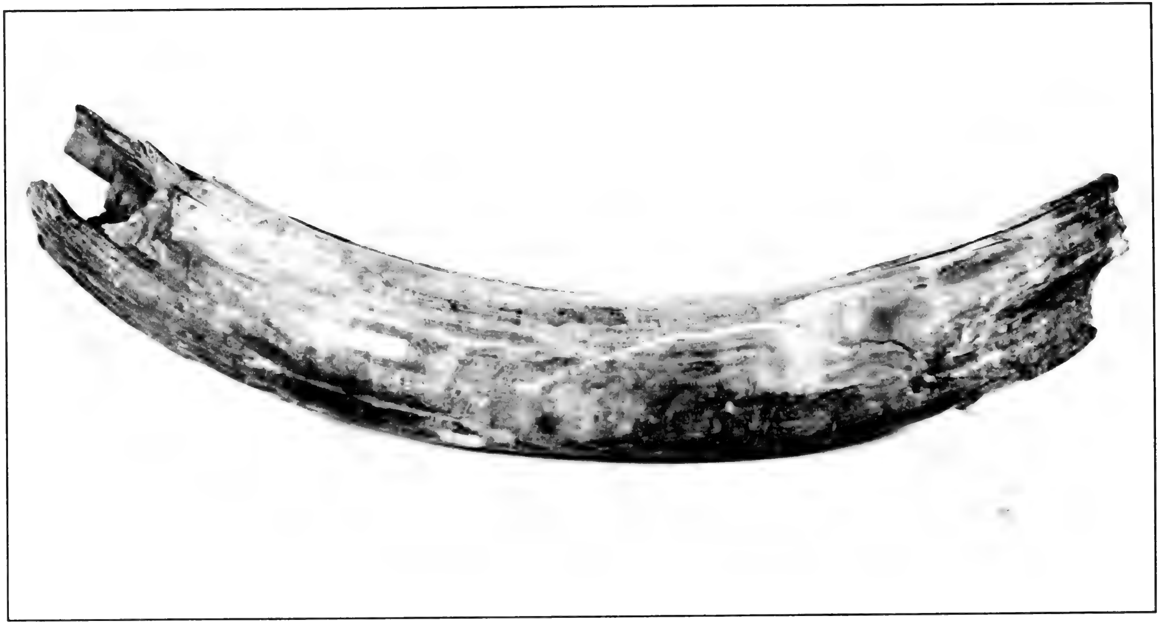

FIGURE 3: Side view of a partial mammoth (Mammuthus sp.; NMC 11833) tusk from Cape James Ross, Melville Island. Collected by members of Stefansson's party during the Canadian Arctic Expedition.

FIGURE 4: Fragment of the left side of a saiga antelope (Saiga tatarica; NMC 12090) cranium with horncore from Baillie Islands.

HOLOCENE VERTEBRATES

Following the megafaunal extinctions near the end of the last glaciation, we are left with the modern vertebrate fauna of the Canadian Arctic Islands. It is worth considering this Holocene evidence carefully because it not only yields information on the changing ranges of various species during the present interglacial, but it has important paleoclimatic implications. In the early Holocene (about 10,000 to 5,000 years ago), several species of vertebrates occupied northern Ellesmere Island. Fielden (Fielden and De Rance 1878), a member of Nares' Royal Navy expedition, collected ringed seal (*Phoca hispida*), collared lemming (*Dicrostonyx torquatus*), caribou (*Rangifer tarandus*), and tundra muskox (*Ovibos moschatus*) specimens from raised-beach deposits near Alert. Perhaps they are of similar age to finds of Oldsquaw duck (*Clangula hyemalis*; Figure 5), narwhal (*Monodon monoceras*), and Peary caribou (*Rangifer tarandus* cf. *pearyi*) from west of Alert that range in age from about 8,500 to 7,000 years ago. Presumably these species were able to migrate into tundra-like areas and coastal waters on the northern margins of the Ellesmere Ice Cap as early as 8,500 years ago, if indeed some did not survive the peak of the Wisconsin glaciation in refuges there. Probably Oldsquaw were migrating to and breeding in northern Ellesmere Island some 7,000 years ago. The species, adapted to tundra lakes and ponds near seacoasts in summer, still breeds in the area (Godfrey 1966). Presumably the narwhal mentioned reached the area during a relatively warm period about 7,000 years ago - well before the ice shelf began to grow about mid-Holocene time. The tusk is 400 to 700 km beyond the range of recently recorded narwhals (Evans 1989).

Farther south, in central Bathurst Island, remains of walrus and tundra muskoxen dating about 7,000 yr B.P. indicate that the ice sheet covering that region during the last glaciation had withdrawn sufficiently to allow immigration of muskoxen - perhaps from refuges in western Banks Island (Harington 1980), as well as a rapid melting of sea ice allowing marine mammals to enter the area. Bowhead whales (*Balaena mysticetus*) had also penetrated that region according to a radiocarbon date on bone from nearby Cornwallis Island (Blake 1970), as well as many other parts of the Arctic Islands during the early Holocene (e.g. Ellesmere (Cape Storm), Devon, Griffith, Somerset and Victoria islands). During the last decade, A.S. Dyke's (1979; personal communication, 1989) field collecting and radiocarbon dating of scores of bowhead remains from raised beaches in the vicinity of

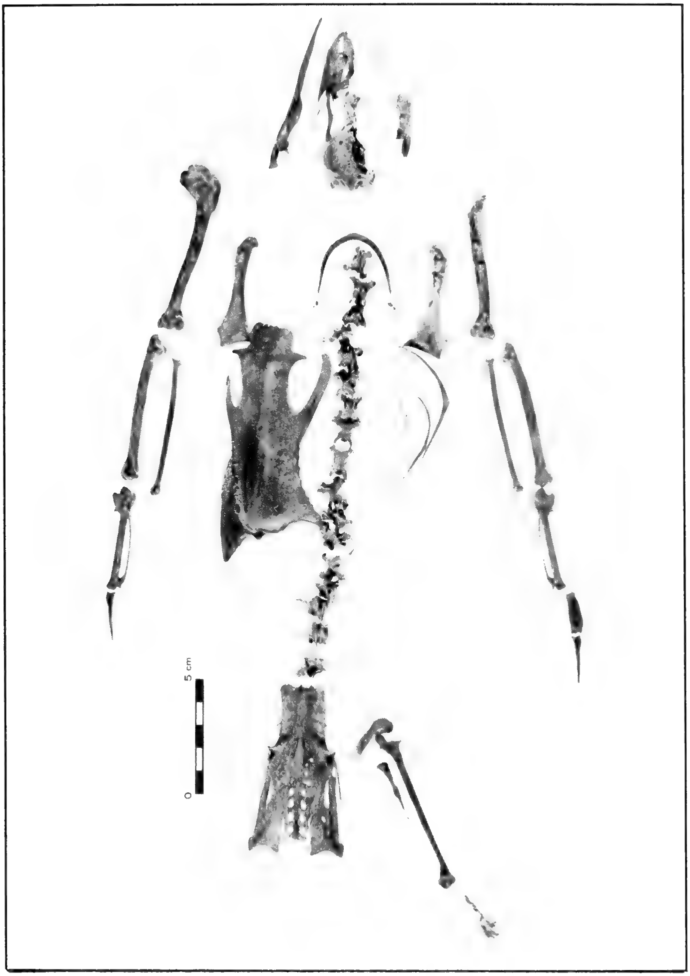

FIGURE 5: Partial skeleton of an individual Oldsquaw duck (Clangula hyemalis); NMC 43777) from Clements Markham Inlet, Ellesmere Island.

Prince Prince of Wales, Somerset and Baffin islands suggest that those whales were relatively common during the summers from about 11,000 to 8,500 years ago, and were somewhat less abundant from 5,000 to 3,000 years ago. Presumably bowheads were largely excluded by relatively solid summer sea-ice conditions in the intervening period, and after 3,000 years ago. It is worth noting that this evidence for more open marine conditions seems to coincide with glaciological records of increasing postglacial warmth 10,000 to 8,300 years ago, following which temperatures reached a plateau until the period of maximum postglacial warmth between 5,000 and 4,500 years ago (Fisher and Koerner 1980). Further, Evans (1989) has summarized glaciological and geomorphological data indicating deteriorating climate in the Canadian High Arctic after about 3,000 years ago.

Because they are rare, or of unusual interest, I have mentioned radiocarbon dates on a few late Holocene (about 5,000 years ago to the present) mammals indicating the presence of polar bears near Prince of Wales Island about 2,000 years ago, lemmings on Bathurst Island at least 4,000 years ago, and bison on Baillie Islands nearly 2,000 years ago.

FUTURE

Existing evidence suggests that discoveries of rich Pleistocene land vertebrate faunas in the Canadian Arctic Islands will be rare. To date, vertebrate paleontologists have relied heavily on Quaternary geologists (who habitually look very closely at surficial deposits and have a good chance of finding fossil bones) for specimens from this vast region - one that is relatively expensive to penetrate and in which paleontological field seasons are necessarily short.

Table 1 shows that field workers in various disciplines have picked up casually many interesting Pleistocene vertebrate specimens from seven different sites on Herschel Island, so a paleontological reconnaissance there has high priority. Another interesting situation is developing in the vicinity of Baillie Islands where saigas survived in probable steppe-like surroundings until near the close of the last glaciation, and where an unusual enclave of bison (probably wood bison, according to the latest evidence) seems to have survived in the late Holocene. It will be interesting to see if paleobotanical clues will be found that can

explain the apparent existence of both steppe-like grassland and wood bison habitat in the area during the late Wisconsin and the late Holocene respectively.

FIGURE 6: Paleobiological collecting at Morgan Bluffs near Jesse Bay, Banks Island in 1982. Jerry Fitzgerald excavates fossils from a peaty layer.

As noted previously, it seems advisable for vertebrate paleontologists to look more closely at the possibility of recovering Pleistocene land vertebrate fossils on Banks Island where rather thick sequences of glacial and interglacial deposits occur, some of which are organic (Harington 1985) (Figure 6). Can we find datable land mammal evidence showing that the area was a Wisconsin refuge for caribou, muskoxen and other species (e.g. Maher 1968)? Can similar evidence be found supporting the existence of refuges elsewhere in the Arctic Islands for migratory birds and land mammals during the last glaciation? We must keep looking.

Remains of Holocene marine mammals scattered on raised beaches throughout the archipelago are already being exploited for their geological and archaeological evidence by workers such as A.S. Dyke and J. Savelle, who are focusing presently on the southern islands of the archipelago. Beyond those values are potentially important paleoclimatic implications stemming from the relationship between marine mammals and their environmental adaptations (Harington 1988). Was there a delay between early Holocene open-water conditions in the southern islands compared to the northern ones? To find out, the investigation must be extended northward.

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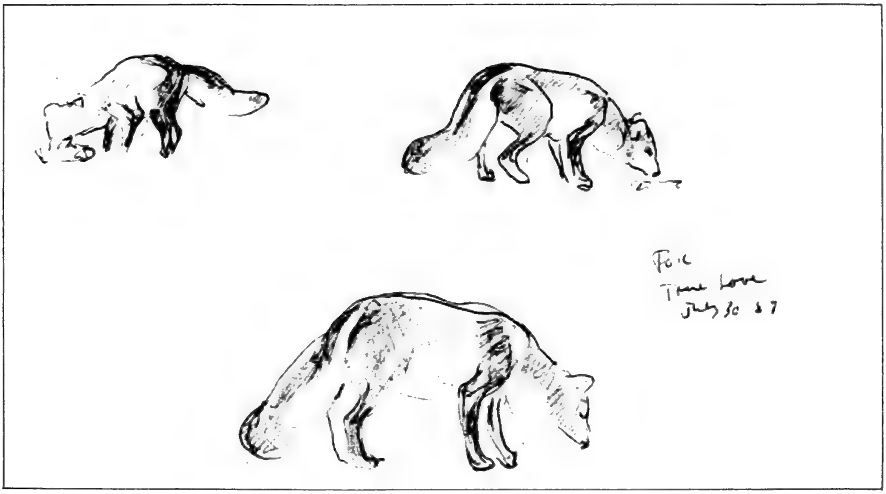

Illustrated by Brenda Carter

TABLE 1: SOME QUATERNARY VERTEBRATE REMAINS FROM THE CANADIAN ARCTIC ISLANDS[1].

TAXA AND SPECIMENS	LOCALITY	REMARKS
Yukon		
Small seal (*Phoca* sp.). Base of left scapula (NMC 25149)	Herschel Island, Pauline Cove (Herschel Loc. 1). Figure 1.1.	Collected in 1973 with marine mollusc shells by C.R. Harington. Possibly of last (Sangamon) interglacial age (Harington, in press).
Large whale, like a bowhead (Cetacea cf. *Balaena mysticetus*). Skull fragment (NMC 17611)	Herschel Island, southwestern part (Herschel Loc. 2). Figure 1.1.	Collected in 1970 by M. Bouchard. Possibly of last (Sangamon) interglacial age (Harington, in press).
Mammoth (*Mammuthus* sp.). Tusk lacking tip (NMC 17612)	Herschel Island, southwestern part (Herschel Loc. 2). Figure 1.1.	Collected in 1970 by M. Bouchard. From a relatively young individual, according to the tusk's smallness.
Woolly mammoth (*Mammuthus primigenius*) Upper molar (PMA P65.17.1).	Herschel Island Figure 1.1.	Collected in 1965 by C.G. Matthews. Late Pleistocene.
Small horse (*Equus lambei*). Partial cranium (NMC 43815)	Herschel Island, northeastern coast (Herschel Loc. 7). Figure 1.1.	Collected by S. Dallimore and S. Wolfe in 1986. In silty sand near top of section (40 m asl). Radiocarbon date: 16,200 ± 150 yr B.P. (RIDDL:SFU-765). (Harington 1989).
Small horse (*Equus lambei*). Second phalanx (NMC 10103)	Herschel Island, Pauline Cove (Herschel Loc. 1). Figure 1.1.	Collected in 1974 by D. Campbell from beach. Probably late Pleistocene.
Small horse (*Equus lambei*). Third phalanx (hoof) (NMC 34408)	Herschel Island, Pauline Cove sandspit (Herschel Loc. 1.). Figure 1.1.	Collected by P.F. Cooper, Jr. in 1973 on surface. Probably late Pleistocene.
Large-horned bison (*Bison priscus*). Right hornsheath (NMC 17708)	Herschel Island, Pauline Cove (Herschel Loc. 1). Figure 1.1.	Collected in 1969 by D.A. Gill from beach. Probably late Pleistocene.
Large-horned bison (*Bison priscus*). Partial left hornsheath (NMC 17709)	Herschel Island, Pauline Cove (Herschel Loc. 1). Figure 1.1.	Collected in 1969 by D.A. Gill from beach. Probably late Pleistocene.

TAXA AND SPECIMENS	LOCALITY	REMARKS
Bison (*Bison* cf. *priscus*). Left ulna fragment (NMC 43816)	Herschel Island, Pauline Cove (Herschel Loc. 1). Figure 1.1.	Collected in 1986 by R. Collier, S.Dallimore and S. Wolfe from beach.
Bison (*Bison* cf. *priscus*). Distal part of right horn-core (NMC 17913)	Herschel Island, Pauline Cove (Herschel Loc. 1.) Figure 1.1.	Collected in 1971 by John Raddi from beach. Probably late Pleistocene.
Helmeted muskox (cf. *Symbos cavifrons*). Right tibia (NMC 17613)	Herschel Island, south-western part (Herschel Loc. 2). Figure 1.1.	Collected in 1970 by M. Bouchard. Probably late Pleistocene.
Tundra muskox (*Ovibos moschatus*). Posterior of cranium with horncores of a very large adult male (NMC 17678)	Herschel Island, central region (Herschel Loc. 3). Figure 1.1.	Collected in 1969 by D.A. Gill from valley bottom west of the island's main lake. Probably late Pleistocene.
Northwest Territories		
Dovekie (*Alle alle*). right ulna (NMC 34551) and sternum of an immature individual (NMC 43813)	Ellesmere Island, 6.5 km north of Cape Storm. Figure 1.21.	Collected in 1975 by W. Blake, Jr. Probably mid-Wisconsin as indicated by six radiocarbon dates on algae and mollusc shells of about 40,000 yrs B.P. (Blake 1980). Immature specimen may indicate a former breeding colony.
Oldsquaw (*Clangula hyemalis*). Most of a skeleton (NMC 43777; Figure 5).	Ellesmere Island, Clements Markham Inlet (82°36'N, 68°31'W). Figure 1.24.	Collected about 1983 by T. Stewart from raised beach deposits about 7,000 yr B.P. Soft tissue still adheres to sternum.
Ptarmigan-like bird (cf. *Lagopus* sp.). Right carpometacarpus fragment (NMC 34816)	Banks Island, Morgan Bluffs near Jesse Bay. Figure 1.9.	Collected in 1977 by J.S. Vincent. Probably from an interglacial about 700,000 yr B.P.
Bird (Aves). Partial feather ("DFTR 86-03")	Ellesmere Island, Thores River. Figure 1.23.	Collected in 1985 by D.S. Lemmen. According to him the feather is probably between 7,700 yr B.P. and about 31,000 yr B.P. (date on associated, possibly reworked mosses).

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TAXA AND SPECIMENS	LOCALITY	REMARKS
Collared lemming *(Dicrostonyx torquatus)*. Right mandible with teeth (NMC 34814) and right mandible (NMC 34815)	Banks Island, Morgan Bluffs near Jesse Bay. Figure 1.9.	Collected in 1977 by J.S. Vincent. Probably from an interglacial about 700,000 yr B.P.
Collared lemming *(Dicrostonyx torquatus)*. Unspecified bone	Ellesmere Island, near Alert. Figure 1.25.	From raised beach deposits. Probably early Holocene (Fielden and DeRance 1878; Harington 1978).
Lemming (*Lemmus* or *Dicrostonyx*). Unspecified bone	Bathurst Island, near Muskox River (75°45'N, 98°32'W). Figure 1.15.	From sediment overlying till. Radiocarbon date: 4,070 ± 140 yr B.P. (GSC-401) (Dyck *et al.* 1966, p. 27).
Polar bear (*Ursus maritimus*). Canine teeth with scattered bones of a skeleton (not collected)	Prince of Wales Island, 19 km north-northeast of Cape Richard Collinson and 2.4 km inland. Figure 1.14.	Collected by A.S. Dyke from raised beach (64 m asl). Radiocarbon date of 1,975 ± 120 yr B.P. (Beta-18929) indicates specimen is not contemporaneous with beach formation.
Ringed seal (*Phoca hispida*). Unspecified bone.	Ellesmere Island, Alert area. Figure 1.25.	From raised beach deposits. Probably early Holocene (Fielden and De Rance 1878; Harington 1978).
Small seal (*Phoca* sp.,). A partial skeleton of an adult (NMC 43817).	Ellesmere Island, Clements Markham Inlet (82°36.5'N, 68°31'W). Figure 1.24.	Collected in 1979 by J. Bednarski from glaciomarine silts (6.5 m asl). Probably Holocene (8,000-2,000 yr B.P.).
Walrus (*Odobenus rosmarus*). Tusk	Cornwallis Island (75°01.2N, 93°34'W). Figure 1.17.	Collected from a raised beach (120-150 m asl). Radiocarbon date: 3,510 ± 50 (GSC-2951).
Walrus (*Odobenus rosmarus*). Anterior cranial fragment with right tusk (NMC 13747)	Bathurst Island, about 16 km west of Goodsir Inlet. Figure 1.15.	Collected in 1973 by D.A. Gill from sediments about 53 m asl. Radiocarbon date: 7,320 ± 120 yr B.P. (I-7796). (Harington 1975).

TAXA AND SPECIMENS	LOCALITY	REMARKS
Narwhal (*Monodon monoceras*). Tusk (NMC 44747)	Ellesmere Island, behind the ice shelf 24 km east-northeast of Cape Woods (82°16'N, 85°20'W). Figure 1.22.	Collected at 34 m asl in 1986 by D.J.A. Evans. A radiocarbon date of 6,830 ± 50 yr B.P. (To -.476) was obtained (Evans 1989).
Bowhead whale (*Balaena mysticetus*). Right tympanic (earbone) (NMC 43536) from a skull	Victoria Island, 6.5 km southwest of Cape Wollaston (71°04.5'N, 118°11'W). Figure 1.8.	Collected in 1982 by J.S. Vincent from a raised beach (21 m asl). Radiocarbon date: 9,285 ± 140 yr B.P. (S-2729).
Large whale, probably a bowhead (Cetacea cf. *Balaena mysticetus*). Skull	Devon Island, 4 km north of the head of Truelove Inlet. Figure 1.20.	In yellow silty sand (38 m asl). Radiocarbon date: 8,270 ± 150 yr B.P. (GSC-991) (Lowdon and Blake 1970, p. 82).
Bowhead whale (*Balaena mysticetus*). Vertebra	Somerset Island, 11 km inland from the mouth of Cunningham River. Figure 1.18.	From the surface of marine silt. Radiocarbon date: 8,990 ± 140 yr B.P. (GSC-450) (Dyck *et al.* 1966, p. 27).
Large whale, like a bowhead (Cetacea cf. *Balaena mysticetus*). Rib	Ellesmere Island, 7.5 km north of Cape Storm. Figure 1.21.	Embedded in beach gravel (23 m asl) and exposed in a gully. Radiocarbon dates: 5,600 ± 60 yr B.P. (GSC-979), 5,420 ± 70 yr B.P. (GSC-979-2), 5,050 ± 180 yr B.P. (GSC-979-3) (Lowdon and Blake 1980, p. 18).
Large whale, probably a bowhead (Cetacea cf. *Balaena mysticetus*). Vertebra	Cornwallis Island, near Resolute (74°42'N, 94°59'W). Figure 1.17.	Sample from sand and gravel of a shingle beach 50 ± 10 m asl yielded a radiocarbon date of 7,380 ± 140 yr B.P. (GSC-1193) (Blake 1970).
Probably a large whale (Cetacea). Skull more than 2 m long	Ellesmere Island, 7.5 km north of Cape Storm (76°24.5'N, 98°30'W). Figure 1.21.	In frozen beach gravel (38 m asl). Radiocarbon date: 7,260 ± 80 yr B.P. (GSC-1498), 6,560 ± 170 yr B.P. (GSC-1498-2), 7,240 ± 80 yr B.P. (GSC 1498-3) (Lowdon and Blake, 1980, p. 18).

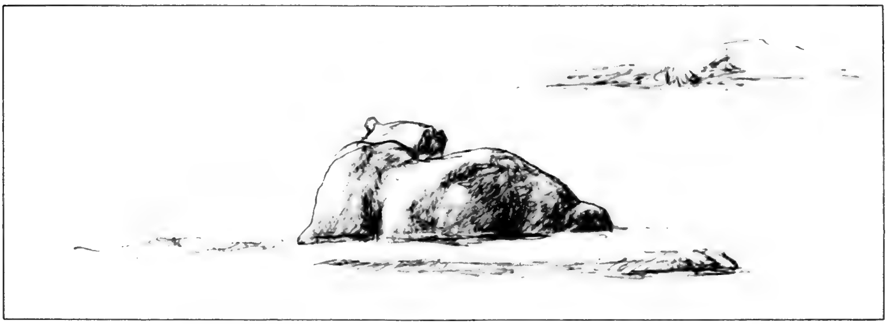
TAXA AND SPECIMENS	LOCALITY	REMARKS
Large whale (Cetacea). Rib	Victoria Island, 29 km north of Ferguson Lake. Figure 1.13.	From sand at 113 m asl. Radiocarbon date: 8,640 ± 140 yr B.P. (GSC-266).
Large whale (Cetacea). Unspecified bone	Griffith Island, southwestern part (74°33'N, 95°30'W). Figure 1.16.	From a raised beach. Radiocarbon date: "5,000 ± 60 B.C., 6,040 ± 60" (P-2141) (see Radiocarbon 19(2):224).
Probably whale (Cetacea). Unspecified bone	Somerset Island. Northwest coast (73°55'40"N, 90°37'30"W). Figure 1.19.	Associated with marine mollusc shells at 76 m asl, and radiocarbon dated at 9,210 ± 120 yr B.P. (S-1405) (Dyke 1983, p. 27).
Mammoth (*Mammuthus* sp.). Tusk fragment (NMC 43785)	Garry Island, Southwestern part (69°28.5'N, 135° 37.5'W). Figure 1.3.	Collected in 1985 by J.S. Vincent. Probably from early Wisconsin outwash deposits.
Mammoth (*Mammuthus* sp.). Tusk fragment (NMC 11833 Figure 3)	Melville Island. Cape James Ross. Figure 1.12.	Collected by members of the Canadian Arctic Expedition (1913-1918). Radiocarbon date: 21,900 ± 320 yr B.P. (GSC-1760) (Kindle 1924; Blake 1974; Harington 1978).
Mammoth (*Mammuthus* sp.). Tibia shaft (NMC 38655)	Banks Island, Ballast Brook area (74°18'N, 123°05'W). Figure 1.11.	Collected in 1976 by L.V. Hills near the top of a 36.6 m bluff in dark sand. Presumably of Banks Glaciation age or later.
Small horse (*Equus lambei*). Left humerus (NMC 10101)	Mackenzie Bay, near "Immerk", man-made drilling platform. Figure 1.2.	Specimen donated by R. Choquette in 1973. It was dredged from beneath about 3 m of water and 13 m of sea-bottom sediment. Probably late Pleistocene.
Small horse (*Equus lambei*). Right radius (NMC 13741)	Richards Island, Ya Ya Lake. Figure 1.4.	Collected in 1972 by A.M. Martell. Probably late Pleistocene.

TAXA AND SPECIMENS	LOCALITY	REMARKS
Small horse (*Equus lambei*). Right metacarpal	Summer Island, north side (69°36.4'N, 134°53'W). Figure 1.4.	Collected in 1986 by J.S. Vincent from beach. Sediments exposed nearby are Kidluit (last, or an earlier interglacial) or Kittigazuit Formation sediments underlain by till of the Toker Point Stade.
Peary caribou (*Rangifer tarandus* cf. *pearyi*). Left antler of an adult male (shed) (NMC 42302)	Ellesmere Island, north end of Piper Pass. Figure 1.24.	Collected about 1983 by T. Stewart. Radiocarbon date: 8,415 ± 135 yr B.P. (S-2501) (Stewart and England 1986).
Caribou (*Rangifer tarandus*). Right mandible fragment with teeth (NMC 17685)	Banks Island, Masik River area (71°35'N, 123°27'W). Figure 1.7.	Collected in 1969 by M. Kuc from a laminated sand with plant remains. Possibly late Pleistocene or early Holocene.
Caribou (*Rangifer tarandus*). Metapodial fragment (NMC 10500) and antler fragments (NMC 10499)	Baillie Islands. Figure 1.5.	Collected in 1965 by J.G. Fyles. Heavily water eroded.
Bison (*Bison* sp.). Third cervical vertebra	Richards Island, northern part (69°29.8'N, 133°54.3'W). Figure 1.4.	Collected in 1986 by J.S. Vincent from the surface of the Kidluit Formation sediments (last or older interglacial), and could have come from those sediments.
Probably wood bison (*Bison bison athabascae*). Partial right hornsheath (NMC 17505). There may be earlier bison remains too (NMC 10501-10505, 12086-12088, 17503-17504)	Baillie Islands, eastern shore. Figure 1.5.	Collected in 1969 by V. Rampton and J.G. Fyles on the beach. Radiocarbon date: 1,810 ± 90 yr B.P. (I-5407) (Harington 1980). Suggests that an enclave of wood bison may have existed recently near the Beaufort Sea coast.
Saiga antelope (*Saiga tatarica*). Left posterior portion of cranium with left horncore (NMC 12090; Figure 4)	Baillie Islands. Figure 1.5.	Collected in 1969 by J.G. Fyles on the beach. Radiocarbon date: 14,920 ± 160 yr B.P. (Beta-25119 ETH-3898). Indicates that saigas survived in northeastern Canada until near the close of the Wisconsin glaciation.

TAXA AND SPECIMENS	LOCALITY	REMARKS
Tundra muskox (*Ovibos moschatus*). Metapodial (sacrificed for radiocarbon dating)	Banks Island, Bernard River. (73°23'N, 120°54'W). Figure 1.10.	Collected from a gravel bar on the river. Radiocarbon date: >34,000 yr B.P. (S-288) (Maher 1968).
Tundra muskox (*Ovibos moschatus*). Right horncore with part of right side of brain case of a female (NMC 34511)	Bathurst Island, 16 km west of Goodsir Inlet. Figure 1.15.	Collected in 1976 by R. Popko and D.R. Gray. Apparently washed into creek bed from sediments nearby. Radiocarbon date: 6,725 ± 130 yr B.P. (I-10919) (Harington 1980).
Tundra muskox (*Ovibos moschatus*). Right mandible with teeth of an adult (uncatalogued)	Bathurst Island, approximately 16 km west of Goodsir Inlet. Figure 1.15.	Collected in 1973 by J.S. Tener from a peat hummock. Radiocarbon date: 2,950 ± 90 yr B.P. (I-9996) (Harington 1980).
Tundra muskox (*Ovibos moschatus*). Left tibia (NMC 17909)	Bathurst Island, 16 km west of Goodsir Inlet (75°43'N, 98°25'W). Figure 1.15.	Collected in 1975 by D.A. Gill from peat bed exposed in creek. Holocene?
Tundra muskox (*Ovibos moschatus*). Cranium, left humerus and partial right humerus of an adult male (NMC 44364)	Banks Island, Jesse Bay. Figure 1.9.	Collected in 1982 by C.R. Harington and G.R. Fitzgerald from surface sediments north of Morgan Bluffs. Holocene?
Tundra muskox (*Ovibos moschatus*). Left pelvic fragment (NMC 11337)	Banks Island, southwest coast 14 km north of Masik River. Figure 1.7.	Collected in 1963 by J.G. Fyles near the base of a 1.5 m layer of alluvium overlying a sand terrace. Plant debris enclosing the bone was radiocarbon dated at 10,600 ± 170 yr B.P. (GSC-240) (Harington 1978).
Tundra muskox (*Ovibos moschatus*). Basiocipital bone (BM(NH) M 3719; Figure 2)	Ellesmere Island, near Alert. Figure 1.25.	From raised beach deposits. Presumably early Holocene (Fielden and DeRance 1878; Harington 1978).
Tundra muskox (cf. *Ovibos moschatus*). Rib fragment (NMC 43784)	Garry Island, southeastern part (69°28.5'N, 135°37.5'W). Figure 1.3.	Collected in 1985 by J.S. Vincent. Probably from early Wisconsin outwash deposits.

TAXA AND SPECIMENS	LOCALITY	REMARKS
Large mammal (Mammalia). Probably part of a limb bone (like a horse or bison metapodial) (NMC 45295)	Richards Island, Near the northern tip (69°43'N, 134°28'W). Figure 1.4.	Apparently collected in 1987 from a 10-cm diameter nearshore drill hole (via S.R.Dallimore). From about 28 m below sea level in frozen gray organic sand. Possibly from the Kidluit Formation or older Kendall Sediments. Last interglacial or earlier.
Medium-sized mammal (Mammalia). Three fragments of cortical bone from a limb(?) bone (NMC 38656)	Banks Island, Duck Hawk Bluff (71°58'N, 125°40'N). Figure 1.6.	Collected in 1983 by J.S. Vincent and attributed by him to the Morgan Bluffs Interglaciation (about 700,000 years old).

[1] This list focuses mainly on land vertebrates older than 5,000 years. Herschel Island is included as one of the Canadian Arctic Islands, as are some of the islands near the mouth of the Mackenzie Delta, as well as Baillie Islands.



Illustrated by Brenda Carter

RATES OF DECAY OF MAMMALIAN REMAINS IN THE PERMAFROST ENVIRONMENT OF THE CANADIAN HIGH ARCTIC

Antony J. Sutcliffe[1]

Abstract: In the permafrost environment mammalian remains, which at lower latitudes would decay rather quickly, are often preserved for a very long time. In the permafrost itself complete carcasses may survive almost indefinitely; for example those of mammoths and bison from Siberia and Alaska, some of which are over 40,000 years old.

Although only a few carcasses of such antiquity have been found in Canada, mammalian skeletal remains with soft tissues less than 1,000 years old are widespread in the floor-debris of Thule houses throughout the High Arctic, and there are instances of complete Thule Inuit bodies about 500 years old from Alaska and Greenland.

Mammalian remains may also survive for a long time on the ground surface, although it is not possible to generalize about how quickly decay will occur, since this varies locally (even within the same specimen) in relation to microclimatic conditions. On a dry scree, soft tissues commonly survive on the lower surface of a bone after they have disappeared from the upper; whereas in a damp situation they decay on the lower surface first. Exposed surfaces of bones tend to weather more quickly than those that are sheltered, with distinct zones of lichen and algal growth respectively.

A series of dated mammalian skeletal remains from the Canadian High Arctic provides an indication of the length of time that, under the most favourable conditions, bones can survive on the ground surface. At the Thule archaeological site of Brooman Point, Bathurst Island, bones and bone artifacts are well preserved after 800 years; and an Independence walrus-ivory harpoon head is almost perfect after more than 3,000 years. Well-preserved whale bones on raised beach ridges at diverse localities carry the record of surface remains back 9,000 years.

Résumé: Les vestiges de mammifères se conservent souvent très longtemps dans un environnement de pergélisol, alors que, sous des latitudes inférieures, elles se détérioreraient assez rapidement. Dans le pergélisol même, des carcasses complètes peuvent demeurer intactes presque indéfiniment; par exemple, parmi celles de mammouths et de bisons de Sibérie et d'Alaska, quelques-unes datent de plus de 40 000 ans.

Bien que seulement quelques carcasses aussi anciennes aient été découvertes au Canada, les restes squelettiques de mammifères, avec des tissus mous, datant de moins de mille ans, sont largement répandus dans les débris du sol des habitations de Thulé dans tout le Haut-Arctique. On a également trouvé des corps complets d'Inuit de Thulé datant d'environ 500 ans, qui viennent de l'Alaska et du Groënland.

Les restes de mammifères peuvent aussi se conserver longtemps à la surface du sol, bien qu'il soit impossible de donner des règles générales sur la vitesse de dégradation, car elle varie localement (même dans un seul spécimen) selon les conditions microclimatiques. Dans des conditions sèches, les tissus mous subsistent ordinairement sur la surface inférieure de l'os après être disparus de la surface supérieure, tandis que, dans des conditions humides, ils se désagrègent d'abord sur la surface inférieure. Les surfaces exposées des os ont tendance à plus rapidement que celles qui sont couvertes, accompagnées de prolifération de lichens et d'algues.

Une série de squelettes datés de mammifères, provenant du Haut-Arctique canadien, apporte des indications sur le temps de conservation les os peuvent s'altérer à la surface du sol, dans les meilleures conditions. Sur le site archéologique de Thulé à la pointe Brooman, sur l'île Bathurst, il y a des os et des artéfacts en os qui sont encore bien conservés après 800 ans; une tête de harpon en ivoire de morse de l'Indépendancien est en presque parfait état après lus de 3 000 ans. Des os de baleines sur des cordons littoraux élevés, à divers endroits, sont bien conservés et détiennent le record de temps pour des restes de surface, avec 9 000 ans.

INTRODUCTION

At middle and low latitudes, mammalian carcasses lying on the ground surface soon decompose because of biological processes and weathering. Even bones seldom survive for more than a few decades, their decomposition products becoming potentially available, via the lithosphere, for biological recycling. Only if buried may they sometimes be indefinitely preserved and, even then, it is unusual for their soft parts to survive. The 2,000 year old

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Iron Age human burials from Danish peat bogs (Glob 1973) and the Upper Pleistocene woolly rhinoceros carcasses from the salty ozokerite deposits of Starunia, eastern Europe (Nowak *et al.* 1930) preserved by unusual chemical conditions, provide notable exceptions.

In the permafrost environment of high latitudes and high altitudes, a totally different state of affairs exists. Bones may survive on the ground surface for thousands of years; and frozen carcasses and other soft parts of mammals and even birds, of diverse ages from Upper Pleistocene to present, are widespread in the underlying sediments.

Best known discoveries of mammalian soft tissues preserved by freeze-related processes come from the northern hemisphere, where the greatest expanses of permafrost occur. However, there have also been some remarkable finds in the southern hemisphere. These include: the 13,000 year old fragments of ground-sloth skin from the Cave of Ultima Esperanza, Patagonia, which Harris (Sutcliffe 1985) concluded had been freeze-dried; the magnificently preserved 500 year old clothed body of an Inca child from an altitude of 5,400 m on El Plomo Peak, Chile (33°S) (McIntyre 1973); and seal carcasses from the ground surface of the "dry" valleys of Antarctica (Dort 1975).

In the northern hemisphere, permafrost underlies a vast circumpolar area extending through Alaska, northern Canada, Greenland, Spitsbergen, northern Scandinavia and Siberia (where it reaches its greatest known depth of 1,450 m at the Shalagonski Settlement in northwestern Yakutia). The southern limit of continuous permafrost varies from 68°N in Alaska to as far south as 59° in Siberia and 55° in Canada's Hudson Bay region. South of these regions there is a further zone of discontinuous permafrost of varying width (Péwé 1969). Mammalian (including human) remains, with their soft parts preserved by freezing to various degrees, have been found in the continuous permafrost zones of all the above-mentioned land areas; but rarely in the northern part of the discontinuous permafrost zone.

These remains are not all of the same age, but range over a considerable period. The earliest mammal-related frozen material pertinent here are excellently preserved small mammal droppings from the Miocene-Pliocene Beaufort Formation of Meighen Island, N.W.T. (79°N), although these may owe their preservation to the peaty nature of the matrix (which also contains well-preserved plant and insect remains) rather than to freezing. So far no remains, even bones, of the animals concerned have been discovered, but the deposit merits continued surveillance.

Most remarkable of all the permafrost discoveries are the Pleistocene carcasses of Siberia and Alaska (map of principal discoveries in Sutcliffe 1985). Animals represented in Siberia include: many woolly mammoth carcasses (e.g. Pfizenmayer 1939; Garrutt 1964; Shilo 1983; Sokolov 1982; Vereshchagin 1974; Vereshchagin and Mikhelson 1981), woolly rhinoceros (Lazarev 1977), horse (Skarlato 1977), bison, wolverine (Vereshchagin 1977), ground squirrel (Vinogradov 1948), vole and ptarmigan. Mammalian carcasses found in Alaska and western Yukon include: mammoth (Anthony 1949), bison (Péwé 1975), pika (Guthrie 1973), extinct muskox (McDonald 1984), black-footed ferret (Youngman 1987), caribou and ground squirrel (Harington 1984). General reviews of these frozen remains are in Guthrie (1972), Péwé (1975) and Harington (1978).

Radiocarbon dates now available for many of these remains fall into two main groups: one (including the Siberian Shandrin and Khatanga mammoths, 'Dima', and a bison from Fairbanks) ranging from about 45,000-30,000 years; and another including a smaller number of remains about 14,000-10,000 years old. The Siberian Yuribei mammoth, with a radiocarbon date of only about 9,700 years, is of Holocene age. In spite of the antiquity of these frozen remains, their state of preservation is often remarkable, allowing detailed histological studies. In the Shandrin and Yuribei mammoths, even larvae of the stomach bot-fly (*Cobboldia*) were preserved (Grunin 1973; Vereshchagin 1982).

A frozen carcass of a whale, estimated to be between 2,500 and 200 years old, found in 1954 entombed in the ice-cored moraine of Sveabreen, Ekmanfjord, Vestspitzbergen (78°N) was reported by Dineley and Garrett (1959).

No less remarkable than the mostly Pleistocene frozen remains mentioned above are those dating from the last millennium, many of them of special interest because of their archaeological or historical context. These include clothed Inuit bodies believed to be about 500 years old from Utqiagvik, near Point Barrow, Alaska (71°N) (Dekin 1987) and from Quilakitsoq, near Uummannaq, western Greenland (71°N) (Hansen *et al.* 1985); and the bodies of three crew members of Sir John Franklin's expedition in search of the North-West Passage, who were buried on Beechey Island, southwestern Devon Island (75°N) in 1846 and recently temporarily disinterred for study (Beattie and Geiger 1987).

There are also many mammalian skeletal remains from the last few millennia lying on the ground surface in various stages of decay. Some of the later examples have the more

resistant soft-parts still preserved. The rest of this paper focuses on a more detailed study of these mainly surface remains in the Canadian High Arctic.

THE CANADIAN HIGH ARCTIC

It has long been recognized by Arctic travellers that some mammalian bones seen lying on the ground - especially those of whales and seals on the raised beaches and bones at Inuit archaeological sites - are of considerable age. The abundance and beauty of the lichens growing on them has also attracted attention. More than a century ago Nares (1878) recorded "... we found at Cape Sabine, Ellesmere Land, the remains of several ancient Eskimo encampments as well as an old sledge made of walrus bones, with cross-bars of narwhal horn, completely lichen-covered and of such antiquity that the bones were friable ...". Greely (1886), described the differential preservation of a bone from northern Ellesmere Island: "... evidently it is part of a native sledge of the cellular bone of a whale ... One side was covered with lichens ... and was so affected by exposure as to be almost unrecognizable as bone. The reverse side, however, showed plainly the marks of the knife".

Although scientists, especially archaeologists, working in the Arctic have long since become familiar with the differing states of preservation of ancient mammalian remains such as these, so far no general review of the rates and processes of decay involved (including whether the ages of bones can be accurately estimated from their appearance) has been attempted. The Canadian Arctic Islands offer an ideal environment for such a study. Not only do they provide a vast area of mostly glacier-free permafrost terrain that for thousands of years has been a rich ground for the accumulation of mammalian bones, but their remoteness has protected them from human interference of the sort that, in a populated area, would long ago have led to their destruction. Diverse methods of dating (radiocarbon and altimetric methods for the remains from the raised beaches, archaeological and historical evidence for the later remains) now provide a chronological framework reaching back nearly 9,000 years to which the various stages of decay can be related.

In a region where shortage of organic nutrients is a major factor inhibiting plant growth, the rate at which the decomposition products of bone can return to the soil is significant to plant-productivity. In some arctic desert areas (e.g. Brooman Point on Bathurst Island),

patches of moss provide a certain indicator of underlying fragments of bone, some so small that they would otherwise be difficult to locate. In the less severe environment of nearby Polar Bear Pass, the almost-decayed carcass of a muskox (dead about 12 years, with the skeleton and most of the stomach contents still preserved) is surrounded by a luxuriant growth of grass and poppies on an otherwise poorly-vegetated slope.

STUDY AREA AND ACKNOWLEDGEMENTS

Travelling in the High Arctic is not simple, and the pursuit of scientific work, especially a topic such as this, is largely dependent on the support of others. I gratefully acknowledge the facilities, guardianship, guidance and encouragement received during expeditions based at Resolute in 1975 and 1979, which allowed me to examine in the field a long series of mammalian skeletal remains, most with chronological data, ranging in age from about 7,000 years to specimens that died only a few hours earlier.

Permission to undertake the 1979 part of this study was granted by the Government of the Northwest Territories.

Air transport between sites was provided by the Polar Continental Shelf Project.

Len Hills and John Matthews allowed me to join their 1975 expedition to Meighen Island (79°N) described by Stefansson (1921) as "the most nearly barren land I have seen in the Arctic".

Stu MacDonald and David Gill provided hospitality at the National Museum of Natural Sciences High Arctic Research Station at Polar Bear Pass, Bathurst Island (76°N), during 1975 and 1979; providing access to: a raised-beach whale skull now situated, as the consequence of isostatic uplift, 6 km from the sea; bones chewed by wolves; bones and antlers chewed by arctic foxes; muskox carcasses in various stages of decay; wolf and fox droppings; Snowy Owl pellets containing bones; and much other interesting material.

Bob McGhee allowed the writer to investigate mammalian remains encountered during his 1979 excavation of Dorset and Thule culture dwellings at Brooman Point (McGhee 1978, 1980, 1981, 1984A, 1984B). Of special interest from this site is the 800 year old frozen occupation debris found in the floors of several Thule houses. During the course of the

excavation a polar bear conveniently killed a seal on the nearby sea ice, permitting subsequent examination of what was left of that carcass.

Peter Schledermann permitted a similar investigation of mammalian remains, including frozen-floor remains, excavated during 1979 from a Dorset-Thule site at Eskimobyen, Knud Peninsula, Ellesmere Island (79°N), and from a Thule-Viking site on Skraeling Island, Alexandra Fiord (Schledermann 1978, 1981; Arnold and McCullough, this volume). This part of the expedition also enabled me to examine bones around the abandoned Royal Canadian Mounted Police Detachment at Bache Peninsula (occupied 1926-1933) and from the dog enclosure at the Alexandra Fiord Police Detachment (abandoned 1963). A visit to the site where Greely's party tragically spent the winter of 1883-1884 on Pim Island (78°N) (Greely 1886, Powell 1961; Rockwell, this volume) revealed no bones associated with this event. However, the survival of undisturbed canvas and leather fragments on the ground for more than a century, forcefully demonstrates the slowness of decay or organic remains in this arctic environment.

I gratefully acknowledge additional carefully-documented study material, collected by others from the following localities:

From raised beaches: bones or bone fragments of marine mammals from Wes Blake (Cape Herschel, Ellesmere Island (78°N)), Stu MacDonald (Seymour Island (76°N)) and Joseph Svoboda (Devon Island (76°N) and Lake Hazen, Ellesmere Island (82°N)).

From the nineteenth century: muskox, caribou and seal remains (dating from 1855-1890) collected by Cliff Hickey from the ground surface at the *Investigator* site, Mercy Bay, Banks Island (74°N) (Wilkinson and Shank 1975; Parfitt, in preparation), and photographs of remains at this site from W. von Koenigswald; and vertebrae from a muskox shot by Otto Sverdrup in Sverdrup Pass, Ellesmere Island (79°N) during the third week of April, 1899 (Sverdrup 1904), collected by David Gill in 1985, have a uniquely exact date.

Collections of recent caribou and reindeer antlers provide useful comparative data from localities outside the area of the present study: some chewed by these animals and by rodents, collected from Alaska by the Cambridge University Alaska Expedition (1977) and R.E. Nelson in 1978 and 1980; from the mainland Northwest Territories by B. Gordon (1978) and C. Tarnocai (1978); from Spitsbergen by O. Salvigsen (1977) and the Cambridge University Spitsbergen Expedition (1978); as well as my 1971 collection from the Hardangervidda Mountains, Norway in 1971 (Sutcliffe 1973, 1977).

THE EFFECT OF HIGH ARCTIC MICROCLIMATE ON THE RATE OF DECAY OF BONES AND SOFT TISSUES

Let us now look more closely at the way in which mammalian remains disappear from the High Arctic environment. Can their age be assessed from their state of preservation? This is possible to some extent, and there is no High-Arctic archaeologist who has not long been familiar with seeing bones of similar ages and in similar environmental situations in like states of preservation. But here, they found, the similarity ends. Not all remains find their way into comparable situations, and microclimatic differences have a profound influence on their condition. In such studies it is also necessary to consider whether the remains being studied have always rested at the same place and in the same orientation, or whether they have subsequently been moved by human (most likely nineteenth or twentieth century people) or other natural processes. Even under natural conditions, the transfer of remains from one microenvironment to another is not unusual. For example, where a bone is carried down into the ground or brought from a horizontal to vertical position around the margins of an active polygon; where it is disturbed by solifluction; where it becomes buried by peat or by sediment; where it is removed from the zone of salt spray along the sea shore by isostatic uplift of the land; or where a pond dries up or becomes flooded. Nevertheless, a vast reserve of material exists that probably lies in its original situation, unaffected by such changes; and the conclusions drawn from the present study are mainly based on this.

The number of possible microenvironments in which mammalian remains may undergo decomposition in the High Arctic is great. One area that has received detailed microenvironmental study is the Truelove Lowland on Devon Island (76°N) (Bliss 1977). The description of the plant communities and map in that book are of particular relevance. For the purpose of the present study, five factors appear to be important in controlling the rates of decay of mammalian remains: (1) whether the remains are buried (including their relationship to the permafrost) or on the ground surface; (2) the amount of moisture; (3) the pH of the surrounding deposits or substrate; (4) the number of months of annual snow-cover (a bone covered by snow for 10 months of the year is likely to survive much longer than one on a windswept hilltop, which may also experience blasting by wind-carried particles); and (5) the degree of exposure to temperature changes and other atmospheric

processes. Commonly not all parts of a bone are exposed to the same environmental conditions. Its underside, in contact with the ground, may remain at freezing-point throughout the summer, whereas its upper surface, baked by the sun, may repeatedly reach quite high temperatures, with associated desiccation.

Plants, by their extraction of nutrients, also contribute to the decay of mammalian remains - their distribution and effect being secondarily related to the environmental zoning just described.

The principal environmental zones investigated during this study (Figure 1) follow.

The Permafrost

Observations on this zone are necessarily limited, since they can be made only where the permafrost has been uncovered, for instance by slumping and in commercial and archaeological excavations. Nevertheless, the condition of mammalian remains preserved in it is often remarkable.

The writer was privileged to examine frozen occupation-debris in the floors of Thule houses being excavated by Schledermann at Eskimobyen and on Skraeling Island, as well as by McGhee at Brooman Point (Figure 2). Household debris included a great variety of mammalian bones (whale, walrus, seal, polar bear, arctic fox, caribou - all with varying amounts of magnificently preserved soft parts, including a seal flipper from Eskimobyen (Figure 3); the entire face and a hind flipper of a walrus, a foot of a caribou, fragments of seal and polar bear skin, bird remains and domestic dog droppings from Brooman Point; baleen, fragments of clothes (including a pair of childs' sealskin mittens tied together with cord from Eskimobyen), and abundant remains of arctic heather and other plants. These remains apparently represent domestic rubbish which had built up sufficiently rapidly on the stone floors of various houses to become permanently frozen - at Brooman Point for more than 800 years; at Eskimobyen probably less than 600 years. All the remains were impregnated with seal oil, which may also have had a preservative effect. This zone of frozen remains was found to end abruptly at its upper limit, at the level to which annual thawing had subsequently penetrated (about 0.4 m at Eskimobyen, and only 0.15 m at Brooman Point).

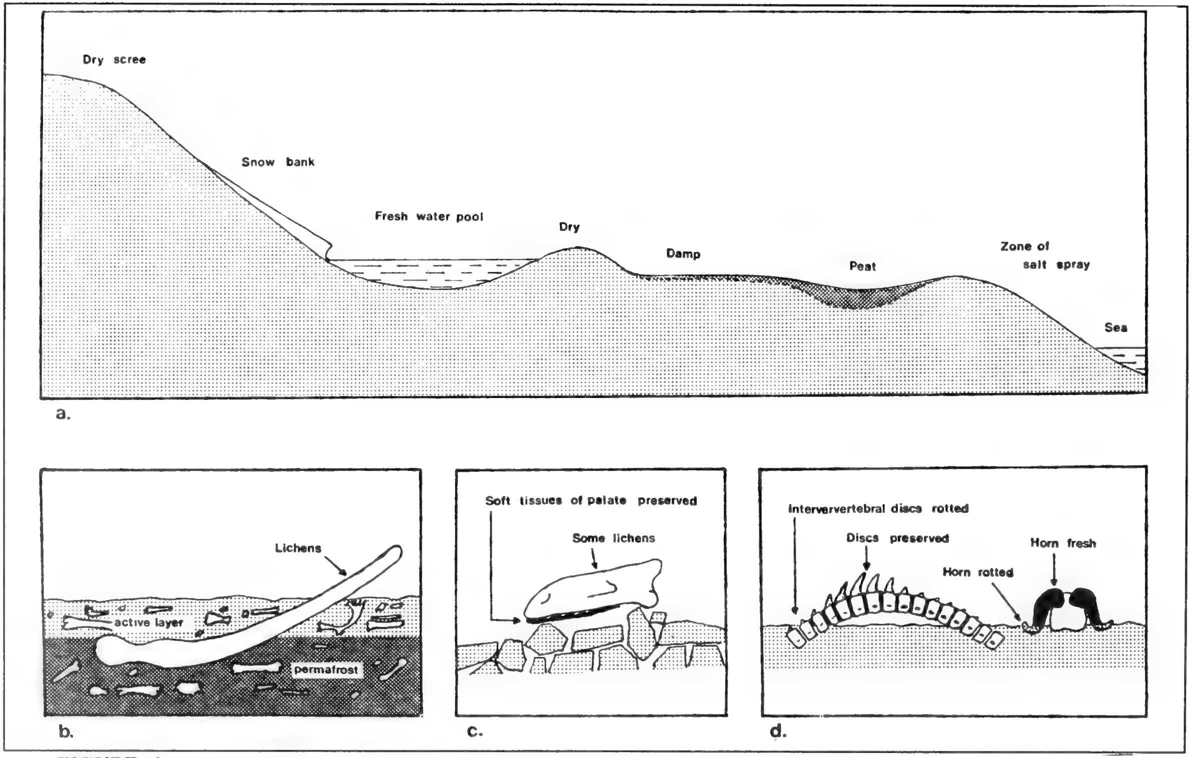

FIGURE 1: (a) Schematic section across an imaginary High Arctic coastal area, showing some of the zones in which bones are likely to show different states of preservation. (b) Schematic section across a deposit where bones occur in three microenvironments (in ascending order): the permafrost, the active layer and above ground. The whale jaw extends through all three zones, and preservation is different in each. Based on floor-debris in Thule houses at Brooman Point, Bathurst Island and Knud Peninsula, Ellesmere Island. (c) Schematic profile of a mammal skull lying on limestone scree; weathered and with lichen growth above, soft tissues of palate still preserved on lower surface. Based on seal skull at Resolute, Cornwallis Island. (d) Schematic profile of a muskox skull and vertebral column, lying on damp ground; horns and intervertebral discs well-preserved above ground, rotted at ground level. Based on remains from Polar Bear Pass, Bathurst Island and from Mercy Bay, Banks Island.

FIGURE 2: Thule house no. 2 at McGhee's site on Brooman Point, Bathurst Island, 1979, before excavation; age about 800 years. Whale jaws and ribs that formerly supported the roof covering, still well-preserved, lie on the ground inside the house wall. Beneath this are frozen floor-deposits containing mammalian bones with soft tissues.

FIGURE 3: Frozen seal flipper in permafrost floor-deposits of Thule house no. 8 at Schledermann's excavation at Eskimobyen, Knud Peninsula, Ellesmere Island, July 1979.

The Active Layer

This deposit was best seen at Brooman Point, where it overlay the permafrost horizon just described. Although containing many well-preserved bones, no associated soft parts survived. Nevertheless, all carried irregular patches of brown staining on their lower surfaces, not present above. Analysis of this substance by G. Jones (Department of Mineralogy, British Museum (Natural History)) gave approximately 35% carbon and 4% nitrogen, suggesting an organic rather than inorganic origin.

The Ground Surface

As previously observed, the state of preservation of mammalian remains lying on the ground varies not only in relation to their age, but also to their microenvironments. Among material dating from the last two centuries it is not uncommon to find that bone decay is proceeding ahead of the decay of associated soft tissues on the more protected surfaces of the same specimens.

Five subenvironments are recognized here.

Dry Scree Slopes and Bare Rock Surfaces

Two stages of decay can be distinguished in this subenvironment - an earlier stage, when some soft parts still survive, and a later one after they have disappeared, leaving only skeletal remains. Most examples studied were on limestone. No data were collected concerning what happens to bones in similar situations on other rock types. A particularly interesting specimen in this category is an imperfect ringed seal skull of uncertain date, found palate downwards on a limestone scree at Resolute on Cornwallis Island (74°N) (Figure 1c). Although the upper surface lacking soft parts, was beginning to flake and already carried a modest lichen growth, the dried soft tissues of the palate were still intact. Remarkably, these also carried a considerable lichen growth.

The archaeological site on the south side of Polar Bear Pass, Bathurst Island, designated OkLg-3 by McGhee, has an associated scatter of fragments of caribou bone resting on a limestone scree and showing preservation (including traces of soft tissues on their lower surfaces, lichens above) reminiscent of the Resolute specimen. McGhee (personal communication) suggests that, unless the site is more than 500 years old, it probably belongs

to the nineteenth century. The condition of these remains makes the latter date the most likely.

The limestone screes of Brooman Point also provide a valuable opportunity for examining more ancient skeletal remains, that have long since lost all their soft tissues. A partially moss-covered Thule dog skull (probably about 800 years old) and a partly moss-covered seal skull, believed to be associated with a nearby Dorset long house (probably 1,000 years old), both intensely desiccated, stand on the surface in a state of near collapse. On the higher beach-ridges and screes are seal and other remains associated with Pre-Dorset/Independence activities (some perhaps 3,000 years old) that have been 'planed down' on their outer surfaces - in some instances to only half their original thickness. The remaining parts are nevertheless in robust condition. The cause of this erosion, which may include wind-blasting, is being studied. A preliminary examination of one of the specimens by scanning electron microscope revealed the presence of great numbers of small tetragonal bipyramids of the mineral weddellite (calcium oxalate, $CaC_2O_4 \cdot 2H_2O$) (Figure 4). Jones *et al.* (1980) obtained weddellite crystals in agar jelly beneath a growing colony of the lichen *Pertusaria corallina*: the role of lichens in the breakdown of bone is to be further pursued in this study.

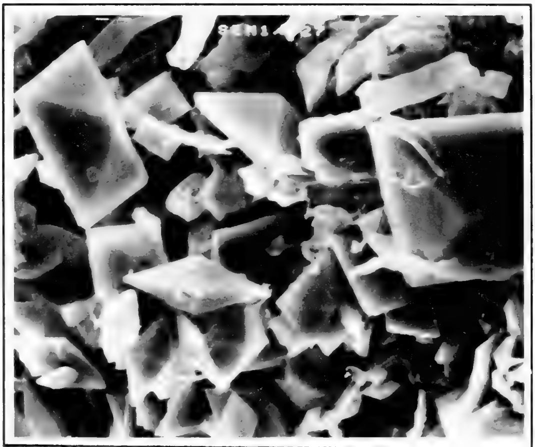

FIGURE 4: Scanning electron microscope photograph (x 1800) of tetragonal bipyramids of weddellite (calcium oxalate, $CaC_2O_4.2H_20$) believed to be a by-product of lichen growth, from a seal bone on the surface of the ground at McGhee's Dorset/Thule site at Brooman Point, Bathurst Island. Photograph courtesy of D. Claugher, British Museum (Natural History).

The extreme aridity of the Brooman Point screes is vividly demonstrated by the condition of the limestone fragments on the arctic desert flat which forms the summit of the peninsula. Some of these show karst-solution features on their upper surfaces, yet underneath they carry botryoidal stalagmitic deposits, suggesting almost immediate

re-precipitation of the dissolved limestone before the solution can even percolate into the ground below.

Damp Ground

Where mammalian remains rest on damp ground, decomposition follows a significantly different sequence of events. Where summer thaw allows sufficient warming, rapid algal growth commonly occurs on the moist lower surfaces of such remains (e.g. on the skeleton of a muskox that died in 1967 near the High Arctic Research Station in Polar Bear Pass, examined in 1975 and again in 1979). Even matted masses of hair associated with the skeleton had a green coating of algae. What happens next depends on the proximity of a particular part of the carcass to the ground, and it is common to see an abrupt change in its state of preservation just above ground level - soft parts surviving in the drier zone above long after they have disappeared from the damper zone below. Instructive instances include an associated vertebral column of a muskox and another muskox skull (Figure 1d), both dead only a few decades, at two localities in Polar Bear Pass. Since the vertebral column was bowed, both ends rested on the ground while the central parts stood clear. Already the intervertebral discs at the ends had rotted, allowing the vertebrae to separate from one another, whereas the central part of the column was still intact. The skull lay so that the horns were mainly above ground, although the tip of one horn penetrated the underlying soil. The exposed parts of the horns were fresh, whereas the tip was extensively rotted and penetrated by the roots of herbs.

An important further instance of this sort of preservation is provided by muskox remains collected by Hickey from the *Investigator* site at Mercy Bay, Banks Island. Here, the ground is strewn with many muskox skeletons killed between 1855 and 1890 by Copper Inuit who had arrived from Victoria Island in order to salvage stores from the abandoned Franklin-search vessel, H.M.S. *Investigator*. The rather exact age for these remains makes them especially valuable for this study. The way in which decay has occurred (soft tissues and horns well preserved above ground, but rotted at ground level) closely resembles that observed in the Polar Bear Pass specimens described above, though with greater lichen development on the exposed surfaces (in part at least a reflection of age).

Mammalian remains that are sufficiently large for parts to stand clear of the ground, as in the above examples, are relatively rare. More numerous are smaller specimens that

lie in contact with the ground. They are typically little weathered and have algal growth on their lower surfaces, being more weathered and with lichens above (Figure 5).

The way in which walrus ivory decays differs considerably from that of bones. It provides a poorer substrate for lichens, and the most common form of breakdown is by warping and exfoliation of the dentine layers.

Peaty and Other Acid Deposits

Peaty deposits are widespread in boggy areas of the High Arctic, occurring even in areas of alkaline base rocks. The growth of such deposits may lead to the incorporation of mammalian remains, which then become susceptible to acid attack. Instructive instances of this were observed at Eskimobyen and in Polar Bear Pass. In a peaty hollow on granitic bedrock beside Schledermann's Thule house no. 3 at Eskimobyen a walrus femur was found at a depth of 10-15 cm. It showed extensive decay of the spongy ends, whereas the surviving outer parts retained their original resilience. Two caribou bones found on the ground surface in Polar Bear Pass (but which had patches of peat adhering, suggesting that they had been disinterred from peat deposits) were deeply eroded. Their remaining parts were nevertheless in fresh condition up to their surfaces, there being no zonation outwards from fresh to decayed bone.

One instance of root marks (solution of the bone surface by the roots of plants) was observed on a caribou jaw found in damp surroundings with herbaceous plant growth near McGhee's archaeological site OkLg-3 in Polar Bear Pass.

Freshwater Pools

This is a difficult subenvironment to interpret since pools that we see today may be younger than bones lying in them; conversely previously existing pools may have dried up. There is also great variation in the nature of bottom sediment. A clear freshwater lake with a rocky bottom and permanent snowbank along its northeast side (an isostatically raised former marine lagoon) at Brooman Point produced part of a polar bear skull (its canines evidently broken out by Thule people) and some seal bones. These remains were well preserved, though with algal growth on all surfaces. In contrast, (although no bones were found in it) there is on Skraeling Island a freshwater pool with a muddy bottom containing worms surrounded by luxuriant vegetation, including sedges and buttercups.

The Sea Shore

A distinct zone of weathering occurs along the sea shore. Watts (1981), describing the Alexandra Fiord area, mentions intense rock-weathering which he thought resulted from salt-crystallization in postglacial time. Surprisingly, this zone appears to be relatively favourable for the preservation of bone. Although lichens form such an important part of the arctic flora, a narrow lichen-free zone occurs along the shore in parts of the study area (e.g. at Eskimobyen and at the old Police Detachment on Bache Peninsula).

Two well-preserved whale skulls, lying on the beach below the Thule dwellings at Eskimobyen, stand out conspicuously because of their whiteness, and there are many smaller specimens in similar condition scattered along the shore. Some factor (perhaps salt spray?) inhibits lichen growth in this environment, and the bones are better preserved than those of equivalent age only a short distance inland. There is, nevertheless, abundant algal growth on the undersides of the bones of this zone. A well-preserved seal skull of uncertain date, collected at low-water from the intertidal zone of a salt water lagoon at Brooman Point, also had a rich algal growth on its lower surface.

Several instances of bone decay commencing before the final disappearance of soft tissues was observed in this shore environment (e.g. among the remains from Bache Peninsula (1926-1933); and a series of walrus vertebrae of uncertain age, with the intervertebral discs well preserved, from the beach at Eskimobyen).

Near the Dorset long house on Knud Peninsula (named by Schledermann "Cove site"), situated close to the sea but about 9 m above it, is a saline pool surrounded, on recently wet ground, by efflorescences of thenardite sodium sulphate, a widespread mineral in polar regions (Tedrow 1977; Watts 1981). The apparent mineralization of some bones from this site is being investigated.

Other Microenvironments

A block of fused hearth material containing much charred bone, collected from the surface of a raised-beach ridge near a Thule house on Brooman Point cannot be included in any of the above categories. It has yet to be studied.

Although, on first consideration, it might be tempting to regard the raised-beach ridges of such localities as Brooman Point as a microenvironment in their own right, they cannot be so classified. Conditions vary greatly from trough to ridge and between the lower and

upper surfaces of bones preserved on them, and each of these zones must be considered separately.

CHRONOLOGICAL CONCLUSIONS

From the observations outlined above, and other data, it now becomes possible to make some generalizations about how long mammalian remains (both soft and skeletal parts) can be expected to survive in the permafrost environment. We have seen that in the permafrost itself soft parts can be preserved almost indefinitely (40,000 years or more in the case of the Pleistocene carcasses from Siberia, Alaska and Yukon), and I will not discuss this zone further. On the ground surface, in contrast, decay will ultimately occur, although it may take thousands of years. An important factor contributing to slowing this process is the shortness of the summer, when such remains are snow-free for only about two months in most of the study area, and the long winter, when the ground is frozen up to the surface together with all the remains lying on it.

The way in which this winter-freeze halts the decay of mammalian remains is well illustrated by the frozen carcass of a juvenile arctic fox, newly exposed by melting snow during the later-than-usual summer thaw in Polar Bear Pass, on 3 July 1979. The fox still had its grey summer pelage from the previous year, suggesting that it had died during the first winter snowfall, not later than about September 1978 - a period of 9-10 months frozen in the snow. Decay during this time appeared to have been halted, even the eyes having the appearance of an animal newly dead. The carcass disappeared the following day, presumably removed by a scavenger.

The speedy disappearance of this carcass vividly demonstrates the potential for destruction of such remains shortly after the death of the animals concerned, so that only a proportion of them survive into a regime of long-term preservation. Some carcass material is removed almost at once by carnivores (of which wolves are the most powerful bone-breakers in the study area) for quick return to the lithosphere via the droppings of the animals concerned.

Much other material survives. Probably the most important factor influencing this is the object's size. Most parts of whale skeletons are too large for destruction by wolves,

although these animals, hunting in packs, can kill muskoxen (Gray 1987) and heavily damage their skeletal remains. Only skulls, vertebrae (especially cervical vertebrae), adult limb bones, metapodials and other robust parts are likely to survive their ravages. Wolves can break caribou bones into small splinters. Bone fragments swallowed by wolves reappear in their droppings, apparently unaltered.

Arctic foxes may cause minor secondary damage to bones of animals killed by wolves and polar bears. I assume that, since the foxes scavenge around camps now, they also scavenged around early Inuit sites at the time of their occupation. Arctic foxes also remove carcasses of lemmings and birds from the environment by eating them.

Caribou are potential destroyers of shed antlers and bones which, in other regions, they have been known to chew to destruction (Sutcliffe 1977).

Remarkably, the consumption of lemmings by Snowy Owls leads to the potentially longer survival of their skeletal remains than if they had died in the open, since bones packed in pellet hair-masses (which occur in great quantity around roosting hummocks) cannot begin to decompose until exposed by the dispersal of this hair, which may take some time.

When all these factors are considered it is immediately apparent that far more skeletal material is preserved in the study area than would be expected in a region of so much carnivore activity. In Zimbabwe, Haynes (1988) has recorded that when other food sources fail, spotted hyaenas return to the bones of elephants that have been dead for some time. Although the analogy of hyaena and wolf feeding-habits is not close, it might be expected that the conditions of natural refrigeration prevailing in the arctic would make it worthwhile for the carnivores there to return to old carcasses for a much longer period than they do in lower latitudes. But this is apparently no so. Although regular inspection of carcass remains by wolves and foxes continues for a long time (personal communication, S.D. MacDonald), there seems to be an early cut off point, after which no further damage occurs. Examples of remains surviving in a more complete condition than might be expected include: carcasses of two muskoxen that died in Polar Bear Pass (one before 1968, the other in 1967), which were extensively splintered and chewed by wolves when fresh but untouched during the study period 1975-1979; splinters of caribou bone, previously mentioned, associated with McGhee's archaeological site OkLg-3, untouched by carnivores, although situated only 200 m from an active arctic fox den; and diverse complete naturally-

shed caribou antlers, especially in Polar Bear Pass - some almost obscured by mosses. This cut off point seems to have a significant place in the bone-decay sequence of the Canadian High Arctic, following which further breakdown is related only to local microenvironmental factors.

In conclusion let us try to establish a chronology for subsequent stages of decay. Since rates vary locally, according to microenvironmental conditions, no simple generalization can be made. The simplest approach is to record the longest time that the various parts of carcasses can survive under the most favourable conditions. There is a substantial amount of data.

We have seen that bones usually survive longer than the soft tissues on them, although it is not unusual for bone decay to commence before the disappearance of the last of these on the more protected parts of the same bones. Soft parts more than a century old are not uncommon, for example on the Mercy Bay muskox remains dating from the period 1855-1890. A small remnant of cartilage on a walrus vertebra from Eskimobyen, believed to be associated with the Thule occupation of that locality, may be substantially older than this, but in general it seems unlikely that much in the way of soft tissue has survived on bones lying on the ground surface for longer than about 250 years.

Although soft tissues tend to be relatively short-lived, the remaining skeletal parts probably survive for a very long time. Four examples of long-term preservation, in order of increasing age follow.

(1) A Thule snow knife from Brooman Point (Figure 5). It is believed to be about 800 years old and to have lain undisturbed on the ground throughout that time. There is substantial lichen growth and some decay above, and better preservation and algal growth below.
(2) A series of seal jaws from the ground surface on Knud Peninsula, believed to be associated with a nearby Late Dorset long house (Schledermann's site SgFm-3) about 1,000 years old, show similar preservational variations, but with more advanced decay, including flaking, on the upper surfaces.
(3) A walrus-ivory harpoon head of Independence Culture I age, more than 3,500 years old, from a flat area of limestone fragments on the hill slope above McGhee's excavation

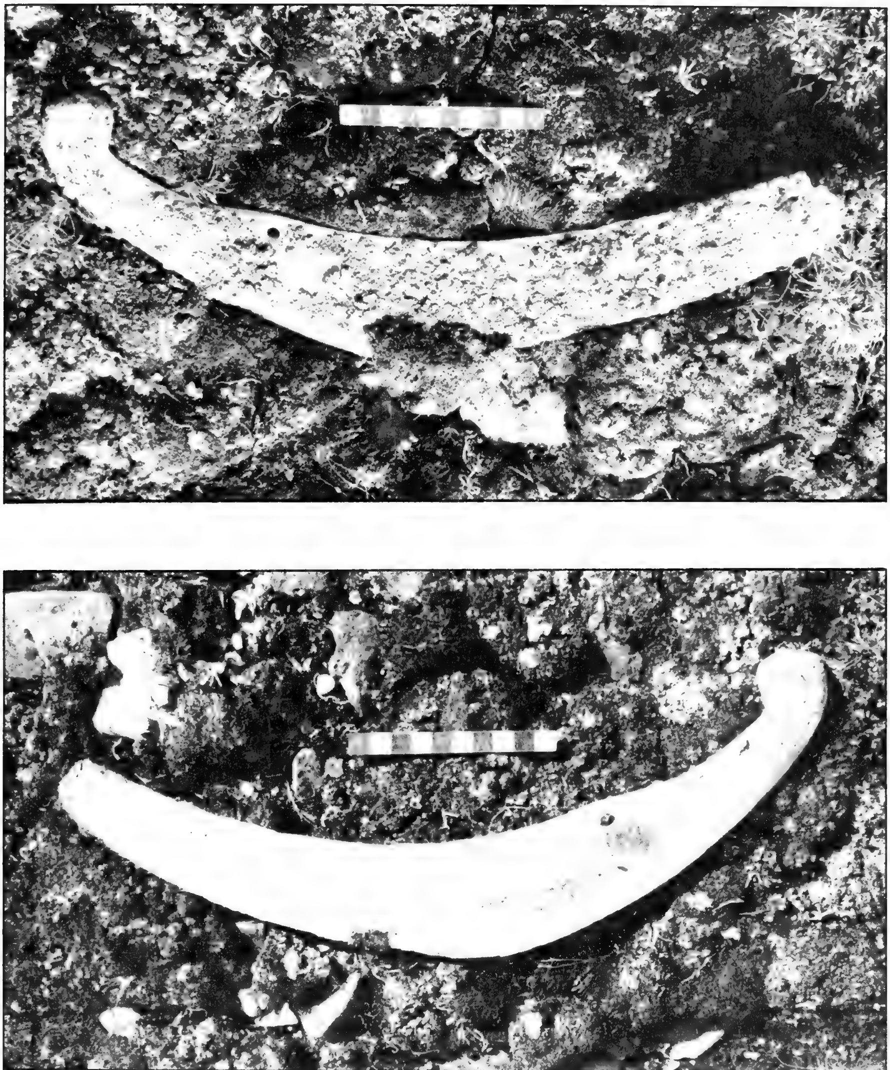

FIGURE 5: Thule snow knife, believed to have been undisturbed for 800 years, on the ground surface at McGhee's excavation site at Brooman Point, Bathurst Island, 1979. (a) in situ, substantial lichen growth on upper surface, (b) specimen turned over to show fresh condition of lower surface.

sites at Brooman Point. It was noticed only because of its moss cover. It is very well preserved.

(4) Remains from the raised beaches. The earliest Inuit sites in the Canadian High Arctic Islands are only about 4,000 years old, so that archaeological evidence cannot be applied to bone studies earlier than this. It is nevertheless fortunate that a great quantity of mammalian remains is available (mostly of whales, associated with raised-beach ridges that are so widespread in the area), which allows the study to reach back to about 9,000 years ago. Before this much of the area was glaciated.

Studies of these flights of beach ridges by Blake and others, using radiocarbon dating of associated driftwood, mollusc shells and whale bones, and involving studies of drifted pumice (Blake 1970, 1975, as well as individual radiocarbon dates published regularly in the Geological Survey of Canada Radiocarbon Dates) provide a detailed record of postglacial isostatic emergence in the Canadian Arctic Islands and, with it, an accurate chronological basis for studying rates of decay of the associated skeletal material - the youngest of which overlaps in time with the archaeological record.

At Cape Storm, southern Ellesmere Island (an area of especially great isostatic uplift), Blake (1975) found that postglacial marine features extended up to 130 m above sea level; emergence between 9,000 and 8,000 years ago having proceeded at 7 m a century, slowing to 0.8 m between 6,500 and 4,500 years ago and less than 0.3 m for the last 2,400 years. He found that whale bones were scattered about at many levels between the present shore and the limit of marine submergence. Some of these were frozen into the ground, others were exposed on the surface where their presence was indicated by vegetation. There were instances of lemmings using hollow parts of bones, above the frost table, as burrows. One of the oldest whale-bone samples collected from Cape Storm, at an elevation of 118 m (Blake 1979), gave an uncorrected radiocarbon date, based on six determinations, of between 8,770 and 9,600 years.

I saw only one raised-beach specimen *in situ*, an undated skull of a bowhead whale in Polar Bear Pass (Figure 6). This and other raised-beach specimens observed from other localities are mostly in a remarkable state of preservation. The 9,000 year limit, where this study must close due to paucity of earlier surface-remains, does not mark the potential survival limit for bones in this environment of the Canadian High Arctic.

FIGURE 6: David Gill (Zoology Division, National Museum of Natural Sciences) inspects a partly-buried skull of a bowhead whale (undated, possibly as old as 9,000 years) on a raised-beach ridge now 6 km from the sea, in Polar Bear Pass, Bathurst Island, June 1979. Although the skull is damaged, the constituent bone is still fresh.

FUTURE WORK

This study of the rates of decay of carcass remains in the permafrost environment is still at an early stage. The program of investigation of microstructure by scanning electron microscope, already commenced, is being extended with special attention to the effects of lichen and algal growth and to secondary mineralization. There are many instances of bones which, although on visual inspection appear to be extensively decayed, have a fresh core or are made up of entirely fresh fragments, commonly with lichen growth between them. There already exists much literature on rock-weathering, including salt-weathering, in the Arctic (Blake 1978; Watts 1979, 1981) that has not yet been explored in this study, despite the fact that it has great relevance.

The role of microenvironmental influence on bone decay needs to be investigated in greater detail in the field; and the study should be extended to the Middle and Low Arctic.

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Illustrated by Brenda Carter

FRESHWATER, SEA AND ICE

A UNIQUE LAKE IN CANADA'S HIGH ARCTIC

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Abstract: Garrow Lake, on the southern tip of Little Cornwallis Island, is unique in a number of ways. It displays mid-water temperatures, attributed to solar heating, that are higher than any other arctic lake described to date. Bottom-water salinities in Garrow Lake are two and a third times those of sea water. These properties have stimulated considerable research on the lake and have given rise to a series of hypotheses to account for its hypersalinity in an area where salt domes do not occur.

Solute rejection during ground-freezing associated with isostatic rebound was hypothesized as the major factor contributing to the high salinities in the bottom of Garrow Lake. This mechanism is based on the intrusion of brines through a permafrost-free talik near the lake's centre. This hypothesis was supported by lake-temperature profiles (1980-1987) and theoretical estimates of the depth of soil temperatures beneath the centre of Garrow Lake based on temperature profiles for the nearby Polaris lead and zinc mine. A new mechanism for multiple-thermocline formation and dissolved-oxygen supersaturation was also displayed in Garrow Lake during years when ice-out failed to occur or was incomplete. During these periods, only the top 5 m of water in the lake mixed, and dissolved oxygen from freezing-out processes accumulated in the 5-10 m deep layer within the lake.

Résumé: Le lac Garrow, sur la pointe sud de la petite île de Cornwallis, est unique de bien des manières. La température de l'eau à mi-niveau, fonction du réchauffement solaire, y est plus élevée que dans tout autre lac de l'Arctique décrit jusqu'à maintenant. La salinité de l'eau du fond du lac Garrow est deux fois et un tiers celle de l'eau de mer. Ces propriétés ont suscité beaucoup de recherches sur le lac, ainsi qu'une série d'hypothèses tentant d'expliquer cette hypersalinité dans une région où on ne rencontre pas de dôme de sel.

On a envisagé que le rejet de la solution pendant le gel du sol, associé à la remontée isostatique, soit un facteur important de la salinité élevée dans le fond du lac Garrow. Ce mécanisme repose sur l'instrusion d'eau salée á travers un talik vers le centre du lac. Cette hypothèse est étayée par les profils de température du lac (1980-1987) et les évaluations théoriques des températures du sol en profondeur sous le centre du lac Garrow reposant sur les profils de température de la mine de plomb et de zinc Polaris, située á proximité. Un nouveau mécanisme de formation de thermoclines multiples et de sursaturation d'oxygène dissout s'est aussi manifesté dans le lac Garrow pendant les années au cours desquelles le déglacement ne s'est pas fait ou a été incomplet. Pendant ces périodes, seuls les 5 m d'eau les plus proches de la surface se sont mélangés et ont dissout l'oxygène provenant de l'englacement et accumulé dans la couche de 5 à 10 m de profondeur à l'intérieur du lac.

INTRODUCTION

Density-stratified High Arctic lakes have been reported for Greenland (Trolle 1913), the Mackenzie Delta (Kovio and Ritchie 1978), Ellesmere Island (Hattersley-Smith *et al.* 1970), Cornwallis Island (Page *et al.* 1987); Ouellet *et al.* 1987) and Little Cornwallis Island (Dickman and Ouellet 1983, 1987). The salinity in the bottom (monimolimnia) of these meromictic (permanently-stratified) lakes is less than that of sea water with the exception of: (1) Sophia Lake (75°06'N, 93°31'W) on Cornwallis Island, N.W.T. with a maximum salinity of 50 g/l; and (2) Garrow Lake (75°23'N, 96°50'W) on Little Cornwallis Island, N.W.T. with a maximum salinity of 82 g/l. Because of their unusual characteristics, these two hypersaline lakes have been the focus of considerable limnological study (Dickman and Ouellet 1983;

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Pagé *et al.* 1984, 1987; Stewart and Platford, 1986; Ouellet *et al.* 1987; Dickman and Ouellet 1987). Several mechanisms drawn from Antarctic work (e.g., Goldman 1970; Harris and Cartwright 1981) have been suggested as explanations for the ontogeny of polar lake hypersalinity. These various hypotheses have concentrated on the process of salinity generation via the "freezing-out" process (Stewart and Platford 1986).

The aim of this paper is to present additional evidence relating to the solute rejection of brines during ground-freezing associated with isostatic rebound. This mechanism is based on the notion of intrusion of brines through a permafrost-free "talik" or chimney near the centre of Garrow Lake. A third possible source of the hypersalinity in Garrow Lake is seasonal groundwater-flow from the active layer. Furthermore, certain aspects of the limnology of Garrow Lake are newly identified.

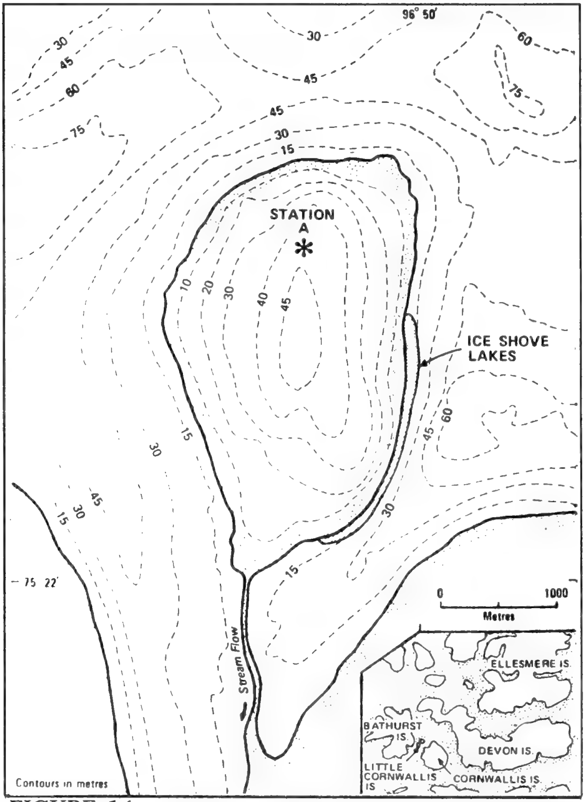

FIGURE 1A: Morphometric map of Garrow Lake, Little Cornwallis Island, N.W.T. with inset of Devon, Little Cornwallis, Bathurst and Ellesmere islands. Details of the Polaris Mine Area were provided by Energy Mines and Resources Canada's Riddle Point NTS map No. 68H-8.

LAKE DESCRIPTION

Garrow Lake (Figures 1A-C), located in the High Arctic on the southern tip of Little Cornwallis Island approximately 95 km from Resolute, N.W.T., is the most northerly hypersaline lake known in the world. It has an area of 418 ha, a

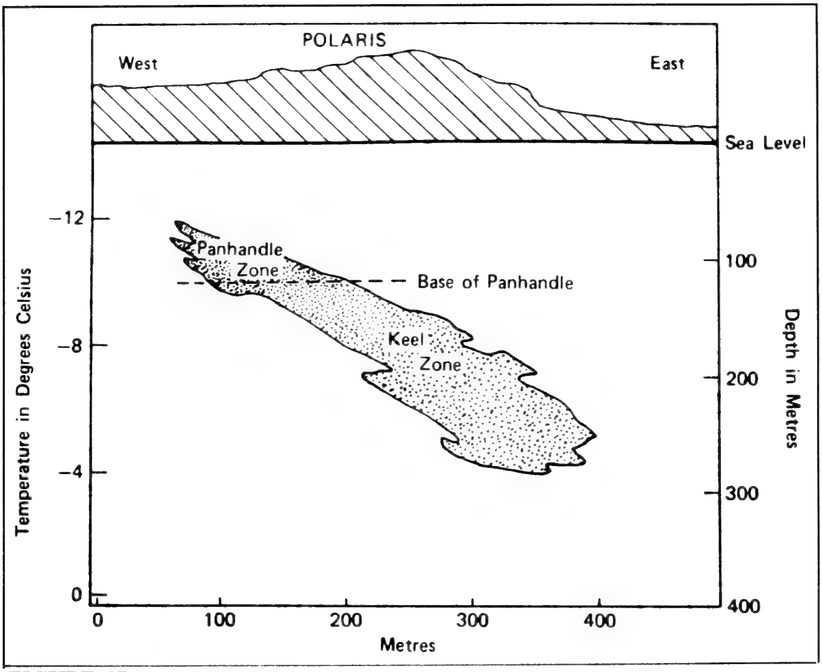

FIGURE 1B: Cross section through the main portion of the lead and zinc ore body at Polaris Mine was based on figures provided by Drake (1984).

maximum depth of 47 m, and is covered by ice (to a maximum thickness of 2.2 m) for more than 11 months of the year. The profundal-zone salinity of this ultraoligotrophic meromictic lake is 75 parts per thousand. This is nearly two and a half times the salinity of sea water. As a result of this high salinity, the dense saline layer of water at 20 m in Garrow Lake traps sunlight and converts it into heat (mean annual temperature at 20 m = 9.1°C) or into chemical energy via photosynthesis (a dense population of phototrophic bacteria have colonized the anaerobic chemocline at 20 m in Garrow Lake (Dickman and Ouellet 1987)).

Because the salinity and hence the density of the water at the chemocline in Garrow Lake are so high, substantial solar-warming can be induced without the density of the water increasing to the point at which mixing with the overlying water masses can occur. As a result, Garrow Lake's chemocline is a significant heat sink. To the best of our knowledge,

no other solar lake in the Canadian Arctic maintains such high winter temperatures. Thus, in a part of the world where the mean annual air temperature is -16.6°C (Anonymous 1982), the water at 20 m in Garrow Lake ranges between 8.9 and 9.1°C. Solar lakes have been discussed for temperate (Cohen *et al.* 1977) and Antarctic areas (Goldman 1970; Harris *et al.* 1979; Harris and Cartwright 1981; Heywood 1977) but this is the first publication on one in the Arctic.

METHODS

Chemistry

Garrow Lake was sampled during August 1980, 1981, 1982, June 1984 and August 1987. All water samples were taken using a 2 litre Van Dorn bottle and transferred to new half litre Nalgene plastic bottles which had been twice rinsed in the water with which they were filled.

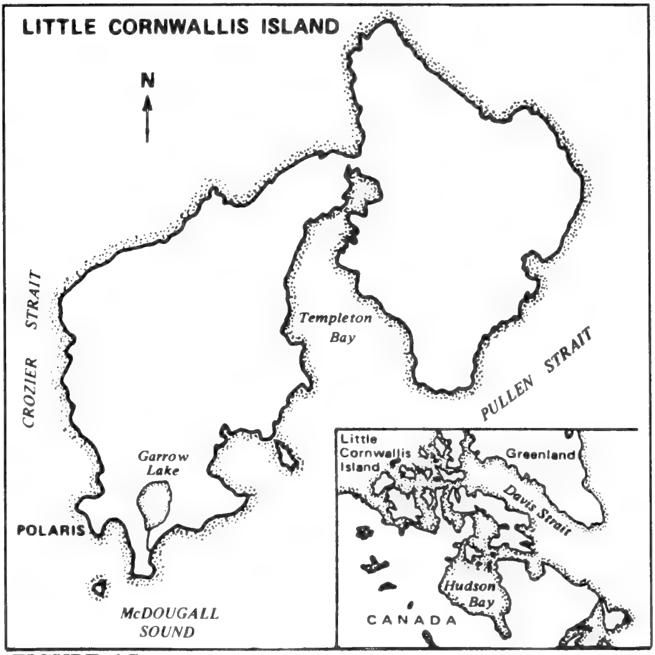

FIGURE 1C: Garrow Lake, Little Cornwallis Island, N.W.T. with inset showing the position of Little Cornwallis Island in relation to Arctic Canada.

Dissolved oxygen, pH, temperature and specific conductivity and salinity were measured in the field using a Hydrolab 4000 and/or a Y.S.I. conductivity meter (model 51A) and a Y.S.I. dissolved oxygen meter (model 33).

Major ions analyzed by INRS-Eau in St. Foy, Quebec and by Canada Centre for Inland and Waters in Burlington, Ontario have been published elsewhere (Stewart and Platford

1986; Dickman and Ouellet 1987; Ouellet *et al.* 1987). Analytical methods used in the laboratory are described by Pagé *et al.* (1984).

Active Layer Analyses

To estimate the salinity of the seasonally-thawed active layer of soil surrounding Garrow Lake, soil cores retrieved on 20 August 1987 were analyzed. The cores were cut into sections and oven dried at 90°C, weighed, dispersed in a measured volume of deionized water for 24 hours and stirred frequently. Supernatant chlorinity was measured with an Orion combination chloride electrode, and the values converted to mg of chloride per gram of soil (C_s). Pore-water chlorinity (C_w) was estimated as $C_w = C_s$ Pb/n, where soil bulk density (P_b) and porosity (n) were assumed to be 1,650 kg/m^3 and 0.3 respectively.

RESULTS

Evidence for a Throughgoing Talik in Garrow Lake

Those arguing that Garrow Lake was injected with saline brines as the Little Cornwallis Island mass rose out of the sea (isostatic rebound) assume the presence of a permafrost-free "talik", or chimney, near the centre of the lake (Dickman and Ouellet 1983; Pagé *et al.* 1984, 1987). In this paper we attempt to provide additional evidence for the talik hypothesis. To test the hypothesis that a talik exists below Garrow Lake, we assembled all of the temperature profiles for 1980-1987 (Figure 2). In addition, the salinity, specific conductivity and dissolved oxygen depth profiles (Figures 3-5) were studied for evidence of convective mixing.

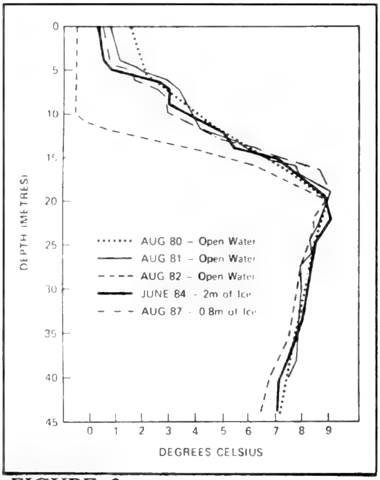

FIGURE 2: Vertical temperature profile for Garrow Lake (1980-87). Except for August, 1982 when the lake was mixing to 10 m, the lake displayed multiple thermoclines at 5 m and 9-17 m. Temperatures were always highest at 19-20 m (8.9-9.1°C) and always decreased to 6.5-7.1°C at the bottom of the lake.

Figure 6 presents a number of predictions for ground temperatures beneath Garrow Lake based on varying the estimated mean ground-

surface temperature and the local geothermal gradient. This was carried out using the following equation (modified from Mackay 1962):

$$[1] \quad T_Z = T_L + Z(*I) - Z(T_L - T_S - (D*I))/\surd Z^2 + R^2$$

where T_Z is the ground temperature (°C) at a depth Z (m) below the bottom of the lake; T_L is the mean annual lake-bottom temperature (°C); I is the geothermal gradient (°C/m); T_S is the mean annual ground-surface temperature (°C); D is the depth of the lake (m).

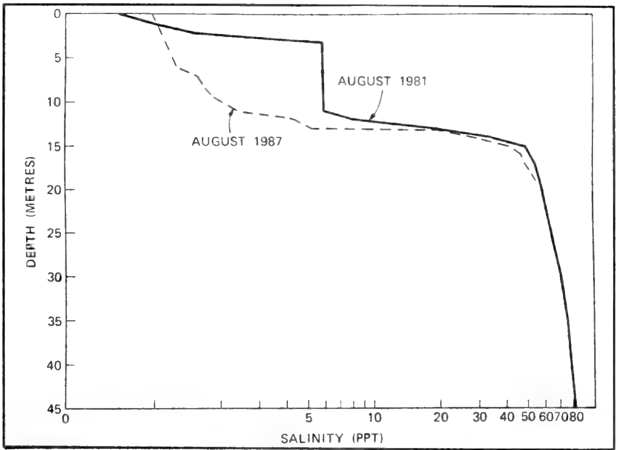

FIGURE 3: Vertical salinity profiles for the deepest point in Garrow Lake on August 1981 and from 20 m of water on 22 August 1987 (log scale used).

The mean annual air temperature at nearby Resolute Bay on Cornwallis Island is -16.6°C (Anonymous 1982) and the mean surface temperature is likely to be slightly warmer (Brown 1972), due primarily to the insulating properties of the winter snow-cover. The temperature of the subterranean sediments were reported by Drake (1984) for the nearby Polaris orebody, which lies near the top of the Thumb Mountain Formation (Figure 1B). At a depth of 400 m below sea level, the temperature of the dolomite, calcite and marcasite, the dominant minerals of Thumb Mountain Formation, approaches 0°C (Drake 1984).

Simulations were run with a conservative value for T_S of -16°C and a more realistic value of -14°C. The minimum radius of Garrow Lake is 900 m and this was used throughout as was a depth of 45 m, providing conservatively low temperatures. The geothermal gradient was initially set at 0.042°C/m, based on a permafrost thickness of 390 m at the Polaris Mine (Drake 1984). According to these calculations (Figure 6, lines A,B),

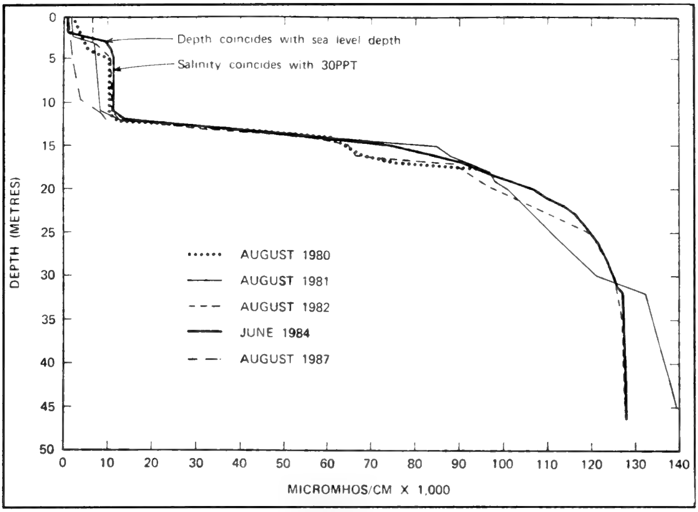

FIGURE 4: Vertical specific-conductivity profiles for Garrow Lake (August 1980-August 1987).

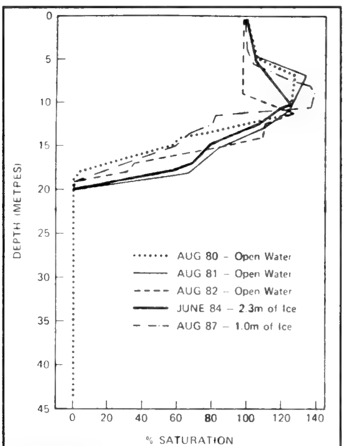

FIGURE 5: Percent saturation (dissolved oxygen) in Garrow Lake (August 1980 - August 1987.

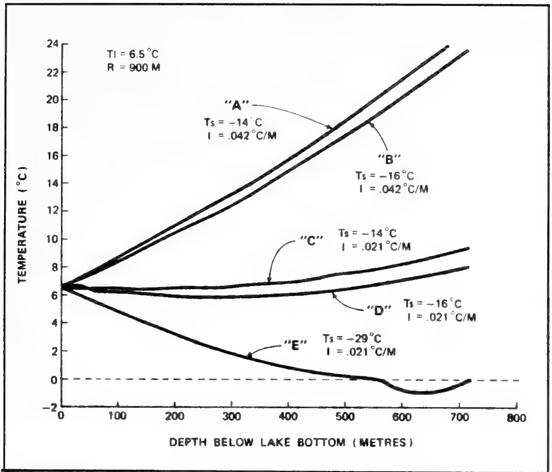

FIGURE 6: Projected temperature - depth profiles for the sediments in the bottom of Garrow Lake near its centre.

A. = mean surface temperature of -14°C and geothermal gradient X 1.0 (results in a throughgoing talik)
B. = mean surface temperature of -16°C and geothermal gradient X 1.0 (results in a throughgoing talik)
C. = mean surface temperature of -14°C and geothermal gradient X 0.5 (results in a throughgoing talik)
D. = mean surface temperature of -16°C and geothermal gradient X 0.5 (results in a throughgoing talik)
E. = mean surface temperature of -29°C and geothermal gradient X 1.0 (fails to result in a throughgoing talik. See text for explanation)

no permafrost exists beneath the centre of Garrow Lake, and none develops even if the surface temperature is greatly lowered.

Since the permafrost thickness at the mine may be anomalously low due to its close proximity to the coast, the same set of conditions were entered with half the geothermal gradient (Figure 6, lines C,D). Temperatures now reach their minimum value 150-300 m below the bottom of Garrow Lake, but these minima are still well above 0°C. Indeed, a mean surface temperature of about -29°C would be necessary before the theorized talik below Garrow Lake would no longer be throughgoing (Figure 6, line E). Because it is so unlikely that annual mean surface temperatures would reach this level, it is reasonable to argue on theoretical grounds that a throughgoing talik exists below Garrow Lake (Figure 7).

Active Layer Analyses

The soil surface salinity was surprisingly high near Garrow Lake, but decreased markedly with depth below the active layer (Table 1).

This vertical chloride distribution suggests that salt is introduced at the surface by precipitation or sea-salt aerosols. Precipitation of chlorinity in 1981 at Mould Bay, N.W.T., which is at a similar latitude and distance from the coast as this study site, ranged from 1.6 to 31.0 mg/ℓ. These values are one to two orders of magnitude smaller than the estimated pore-water salinity at this site. Therefore, considerable drying by evaporation, or influx or airborne salt is required to achieve the observed concentrations. The soil salinity

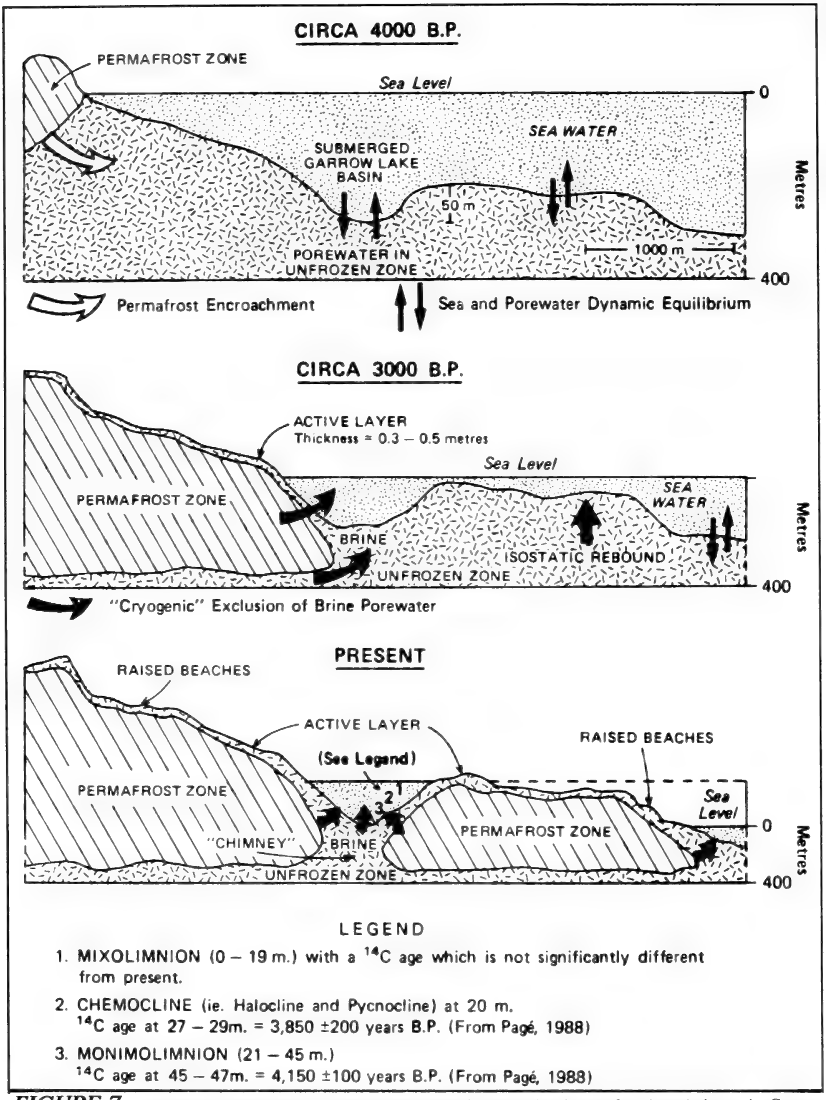

FIGURE 7: Schematic representation of hypothetical changes in sea-level and permafrost boundaries at the Garrow Lake site during isostatic rebound. Permafrost boundaries are conceptual (not measured).

TABLE 1: VERTICAL CHLORIDE DISTRIBUTION NEAR GARROW LAKE.

SAMPLE SITE AND DEPTHS	CS[1] (mg/g)	CW[2] (mg/ℓ)
Core #1 - 30 m from shore		
0-5.5 cm	3.12	17,051
5.5-11 cm	0.23	1,273
11-15.5 cm	0.131	720
15.5-22 cm	0.047	259
Core #2 - 60 m from shore		
0-2 cm	1.29	6,906
2-10 cm	0.409	2,250
10-18 cm	0.281	1,554
18-24 cm	0.270	1,510
Core #3 - 90 m from shore		
0-2 cm	1.732	9,400
2-7.5 cm	0.484	2,664
7.5-13 cm	0.209	1,147
13-20 cm	0.337	1,843

1 Mg of chloride/g of soil.
2 Pore-water chlorinity.

is high relative to precipitation. The active-layer contribution to lake water salinity is therefore minimal due to the low precipitation in this portion of the High Arctic.

DISCUSSION

Ice, Wind and Thermoclines

Garrow Lake displays an unusual vertical temperature profile. In addition to its elevated mid-depth water temperatures, it exhibits multiple thermoclines. During most years, the lake is partially ice-covered during late August prior to its freeze-up in early September. In August 1982, however, the lake was entirely ice free for a 2-3 week period just prior to its freeze-up. Consequently, wind-generated currents mixed the epilimnion to a depth of 10 m (Figure 2) rather than to depths of 5-7 m as was the case in those years when a

partial ice-cover persisted. Thus multiple thermoclines in Garrow Lake are probably the result of deep-mixing episodes during rare ice-free periods. This is an entirely different mechanism for multiple thermocline formation than has been previously described. Traditionally, multiple thermoclines have been ascribed to periods of deep wind-mixing followed by calm and solar-heating which are then followed by a subsequent period of shallow wind-mixing (Hutchinson 1957; Wetzel 1983). In Garrow Lake, the presence of a partial (or complete) ice-cover throughout the year restricts wind-generated currents to the top of the lake's mixolimnion (5-7 m). Only in those rare years when the lake is entirely ice-free for some, albeit brief, period, the ever present wind will cause the mixolimnion to mix to a depth of 10-12 m thus giving rise to multiple thermoclines in Garrow Lake.

The same mechanism that created the Garrow Lake multiple thermocline was probably also responsible for multiple halocline and multiple chemocline formation (Figures 3, 4). In August 1981, the water in Garrow Lake above a depth of 4 m had a salinity of 1-7 parts per thousand (PPT). Below this depth salinity increased rapidly to 60 PPT (approximately two times that of sea water). Below 20 m, salinity increased much more gradually until it reached nearly 2.5 times that of sea water (Figure 3).

During the ice-free period in August 1982, the salinity-profile changed to that represented by the dashed line (Figure 3). For purposes of clarity, the other years have not been superimposed on the depth-salinity profiles. However, the specific conductivity profiles (Figure 4), which mirror the salinity profiles, are provided for each of the five periods that the lake was studied between August 1980 and August 1987. The specific conductivity profiles indicate that once the lake was mixed to a depth of 10 m in August 1982, a brackish-water layer redeveloped at 0-3 m (Figure 4).

In summary, in the absence of late summer ice-cover, the wind mixes the Garrow Lake melt-water with the upper layer of saline water forming a 10 m deep brackish layer of low salinity (Figure 3). During those years when Garrow Lake is partially ice-covered throughout summer and fall, a shallow thermocline develops and the water immediately below the melting ice is nearly fresh.

Freezing-out Processes

During ice formation (freeze-up), dissolved salts and gases are forced out of the ice-crystal lattices and some of these salts and gases are injected into the water below the ice

(Goldman 1970). Once formed, this denser saline water containing high concentrations of dissolved gases begins to sink. This continues until the sinking water-mass reaches a depth of equal density (Goldman 1970).

Both salts and gases formed from "freezing-out" processes remain at this depth or pass into the more saline layer below the uppermost thermocline. Dissolved oxygen below the thermocline climbs to 140% supersaturation in the 5-10 m deep water-layer (Figure 5). Thus supersaturation results from freezing-out and not from photosynthesis, which was shown to be negligible at these depths (Dickman and Ouellet 1987). Oxygen, which accumulates below the thermocline during freezing-out events, is trapped there unless the lake mixes to a greater depth as occurred in August 1982.

The salinity, conductivity, and dissolved-oxygen profiles for Garrow Lake reflect four depth-zones: (1) a 0-5 m mixolimnion with low salinity resulting from ice melt-water. This zone is saturated with dissolved oxygen; (2) a 5-12 m brackish-water zone with supersaturated dissolved oxygen resulting from freezing-out processes; (3) a 12-20 m deep chemocline (chemolimnion) displaying a strong salinity gradient and rapidly decreasing dissolved oxygen; and (4) an anaerobic, deep (20-47 m) monimolimnion with hypersaline water (2.5 times the salinity of sea water, Figures 2-5). Oxygen in the bottom layer (20-47 m) was long ago completely depleted by the decomposition of organic matter which settled into the monimolimnion (Pagé *et al.* 1987). The 25 m deep anaerobic zone (Figure 5) was capped by a mass of phototrophic bacteria (Dickman and Ouellet 1983, 1987).

Since dissolved oxygen from freezing-out events is concentrated above the chemocline, probably this mechanism does not account for the observed hypersalinity of Garrow Lake. This is in contrast to Goldman *et al.* (1967) who reported that the high monimolimnetic salt-concentrations in Lake Vanda, located in the Wright Valley, Antarctica, were due largely to the freezing-out of salts from the lake's surface waters; a process that they referred to as "cryogenic meromixis".

Cryogenic Exclusion of Pore Waters

We believe that freezing-out of marine pore waters (cryogenic exclusion) from below Garrow Lake was most important in establishing the lake's high monimolimnetic salinity. The exclusion of salts would result in ice bodies or vugs of low salinity, such as those reported from the nearby Polaris Mine by Cominco geologists (Pagé *et al.* 1984). Isotopic

analysis of the ice in these vugs indicated that their carbon and oxygen-isotope ratios (Pagé *et al.* 1987) were consistent with the isostatic rebound, freezing-out hypothesis.

Saline pore water trapped within the layers of rock below Garrow Lake would have resulted in salty brines being forced up into the bottom of the lake (Figure 7). According to this scenario, as the island uplifted and the sea receded, permafrost would have aggraded into the lake's watershed, freezing the pore water as it did so. The resulting brines from the freezing-out of salts within the sedimentary pore water would have been concentrated within the talik, and in Garrow Lake itself (Figure 7). Solute rejection during ground-freezing with salt concentration in adjacent pore water, has been reported from laboratory and field studies (e.g. Hallet 1978; Chamberlain 1983; Kay and Groenevelt 1983), so this appears to be a viable hypothesis. However, the extremely high salt-concentrations recorded for Garrow Lake are not known to have been produced in laboratory or field experiments. If the mechanism described is correct, other deep hypersaline meromictic lakes may well be found in the future below marine limit within the Arctic Archipelago.

CONCLUSIONS

1. Garrow Lake displays higher mid-water salinities and temperatures than any Arctic lake described in the published literature.
2. Calculations of the permafrost depth below the centre of Garrow Lake indicated that there is probably a throughgoing talik, or chimney, which would permit the entry of saline brines into the lake's monimolimnion following isostatic uplift, and solute rejection during the accompanying ground-freezing.
3. The active layer of sediment in the Garrow Lake Basin has unusually high salinities (0.05 - 3.1 mg/g) resulting from aerosol inputs and high evaporation and low precipitation levels.
4. Supersaturation of dissolved oxygen at 5-10 m in Garrow Lake was ascribed to freezing-out processes.
5. Multiple thermocline formation in Garrow Lake was ascribed to the incomplete mixing of its epilimnion (upper mixolimnion) during years in which ice-out did not occur or was incomplete.

6. Cryogenic exclusion of brine pore water was probably the chief mechanism responsible for the high monimolimnetic salinities in Garrow Lake.

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ICE/WATER INTERACTIONS AND THEIR EFFECT ON BIOLOGICAL OCEANOGRAPHY IN THE ARCTIC ARCHIPELAGO

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Abstract: Although ice limits light penetration into Arctic seas, it also provides physical stability in early spring to permit primary production at approximately the same season as in lower latitudes. Epontic algae become associated with the ice in the fall and begin rapid growth in early April. The plants are shade-adapted and rapidly produce large populations on the underside of the still-forming ice. Nutrient levels in water which is constantly bathing the under-ice surface are high, but, because of very high concentrations of algae in an ice matrix, diffusion cannot supply all plant requirements. Highest rates of photosynthesis occur during spring tides when tidal currents are strongest. Epontic (under-ice surface) algae support many animals that live on or in the ice, and algal cells are constantly eroding into the water column to support continued development of some plankton animals and to initiate reproduction in others. Strong tidal currents also cause higher rates of algal erosion and better feeding conditions for planktonic animals. Light, currents and food conditions all influence the vertical distribution of plankton animals under the ice. Both diel and seasonal migrations are observed. Young stages of many benthic animals are initially associated with the ice as are young arctic cod. The "double benthos" in the Arctic Archipelago, one upside down, temporary and very productive, and the other still relatively near the surface and the recipient of unused production from above, together contribute to the region's richness in mammals and birds.

Résumé: Bien que la glace limite la pénétration de la lumière dans les mers arctiques, elle y apporte aussi une stabilité physique, au début du printemps, qui permet à la production primaire de se faire à peu près à la même saison que sous des latitudes plus basses. Les algues épontiques deviennent associées à la glace en automne et commencent à croître rapidement au début d'avril. Les plantes sont adaptées à l'ombre et produisent rapidement de vastes colonies sur le dessous de la glace encore en formation. Les niveaux de nutriments dans l'eau qui baigne constamment la surface inférieure de la glace sont élevés, mais, en raison des concentrations très élevées des algues, la diffusion ne peut pas subvenir à la totalité des besoins des plantes. Les taux les plus élevés de photosynthèse se manifestent pendant les marées de printemps où les courants de marée sont les plus forts. Les algues épontiques (sous la surface de la glace) alimentent bien des animaux qui vivent sur ou dans la glace, et des cellules d'algues se détachent continuellement dans la colonne d'eau, participant au développement régulier de certains éléments de plancton et démarrant la reproduction d'autres. Les forts courants de marée causent aussi beaucoup d'érosion des algues, donc de meilleures conditions d'alimentation du plancton. Les conditions de lumière, de courants et de nourriture ont tous une influence sur la distribution verticale des éléments de plancton sous la glace. On y observe des migrations nycthémérales et saisonnières. Les stades jeunes de bien des animaux benthiques sont initialement associés à la glace; c'est le cas de la jeune morue arctique. Le "double benthos" de l'archipel arctique, l'un à l'envers, temporaire et très productif, l'autre encore assez proche de la surface et récupérant la production inutilisée d'en haut, contribue à la richesse de la région en mammifères et en oiseaux.

INTRODUCTION

For those arctic inhabitants wandering over the polar landmass or those that are at least part of the year haul out on the ice, air temperature (which may fluctuate seasonally by perhaps 50 to 75°) introduces a large, though natural element of stress to their existence. In contrast, organisms spending all their life in arctic seas never know temperatures colder than a relatively balmy -1.8°C, and hardly become overheated at 2 or 3°C in mid-summer - especially as cooler waters are only a few metres below the shallow seasonal thermocline. Most of the poikilothermal (cold-blooded) organisms are also psychrophilic (cold-adapted),

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whether autotrophic (primary producers) or heterotrophic (energy consumers). So temperature itself is of small concern in their life.

One manifestation of low temperature, ice, is of great importance in the lives of northern aquatic organisms, however. It alters the physical environment of polar organisms in several unique ways. While forming and melting, it affects the structure and chemistry of the underlying sea water, removing fresh water and concentrating salt in the fall, and diluting the surface water in early summer. Convective mixing is associated with the sinking of the more dense, saltier water during freeze-up, but under ice, wind-driven mixing is of little significance. Lighter water of reduced salinity in spring tends to stabilize the water column and further reduce mixing. In the absence of wind effects, tidal forces become the dominant mixing mechanism in the relatively shallow straits and passages within the Arctic Archipelago. Turbulence normally associated with channelized flow of relatively high velocity is, however, reduced at a boundary layer such as the under-ice surface. But the rising and falling tide near shore, fractures the ice, contributing to the formation of pressure ridges and roughened under-ice topography, that in turn increases turbulence locally. As it thickens and develops a covering of snow, ice itself becomes an insulator against further heat-loss, and its rate of growth slows. At the same time, solar radiation is both reflected from the surface and absorbed by snow and ice in proportion to its thickness, which greatly influences rates of photosynthesis in the underlying water.

That the interface between polar ice and underlying sea water provides a substrate for the development of a distinctive flora and fauna has been recognized since the middle of the last century (Horner 1985A). The organisms associated with the under-ice surface are usually said to be "epontic", and although several other more specific terms have been suggested as an alternative (e.g. "sympagic" as used in Figure 1 taken from Carey 1985), epontic is widely applied and will usually be used here. The traditional under-ice food web is supported by microalgae, consisting predominately of pennate diatoms "attached" to the ice. Also associated with the ice are a variety of animals, notably macrofaunal amphipods, believed to be the principal grazers, and a complex of meio- and microfauna such as harpacticoid and cyclopoid copepods, nematodes, Protozoa and the larvae of a number of benthic invertebrates. However, note that some of the pathways on Figure 1 are uncertain of inferred from other data. Qualitative and quantitative data concerning the functioning of this community are relatively limited.

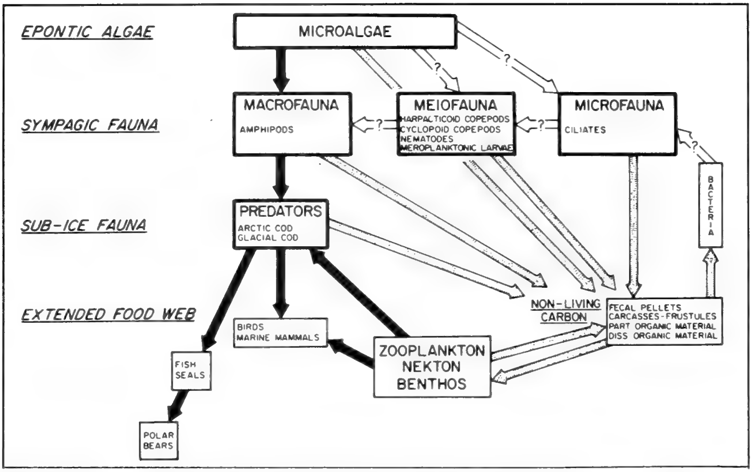

FIGURE 1: A simplified food web to illustrate the major trophic relationships of the ice biota. The energetic linkages are designated at three levels of information: (1) solid arrows = observed; (2) stippled arrows = inferred from other data; and (3) open arrows = hypothesized (reprinted with permission from Carey (1985). Copyright CRC Press, Inc., Boca Raton).

For several years, we have been studying the epontic organisms in relation to their physical environment, and we present here some of our recent work illustrating the importance of under-ice biology in the functioning of arctic food-webs.

DESCRIPTION OF THE ENVIRONMENT

Barrow Strait is the shallowest part of the North-West Passage, there being no water deeper than 200 m between Cornwallis and Somerset islands (Figure 2). To the east the depth increases toward Lancaster Sound and Baffin Bay. Similarly, to the west there is increasing depth towards Viscount Melville Sound and Beaufort Sea. Indeed, shallow sills are characteristic of all the passages through the Arctic Islands so that only surface water can penetrate from the Arctic Ocean to the east. Water enters the Resolute area from the southwest by Somerset Island, from the west from Viscount Melville Sound and from the northwest around Cornwallis Island, and each water-type has slightly different characteristics which can also influence its zooplankton composition (Watson *et al.* 1988).

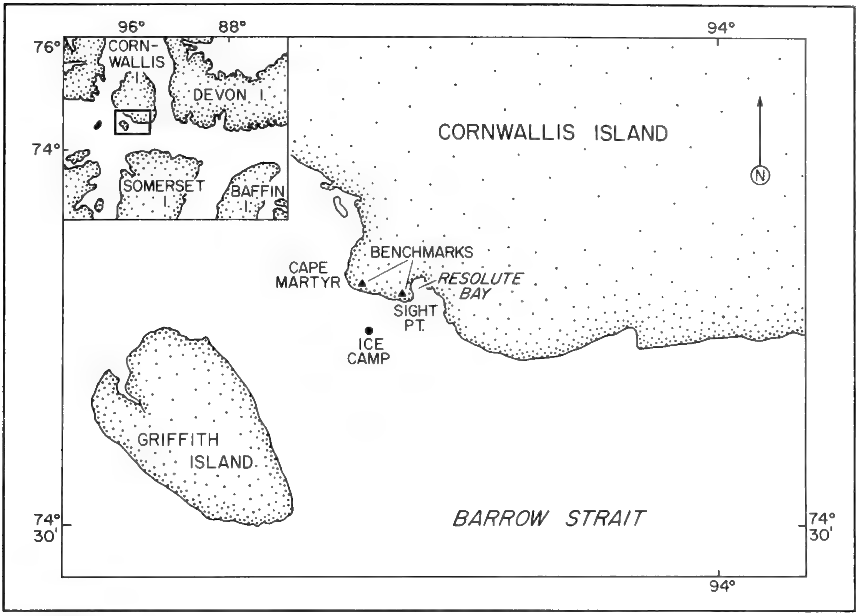

FIGURE 2: Ice camp off Resolute Bay and its location in the central Canadian Arctic Islands.

The maximum tidal range in the Resolute Bay area is about 2 m, and tidal currents from the northwest in excess of 50 m s^{-1} have been observed locally in spring (Cota *et al.* 1987). For further information concerning the general physical oceanography of the region see Prinsenberg and Bennett (1987).

Barrow Strait is normally frozen from October to July, but in 1986 no permanent fast ice was established across to Somerset Island. That year was anomalously warm in December 1985 (5.9°C) and February 1986 (6.0°C) but normal or slightly below for the remaining months between October 1985 and May 1986 (Environment Canada 1986A).

Measurable light returns to the latitude of Resolute during the first week in February and disappears again the second week in November. Continuous light is recorded from the end of April to the middle of August (Environment Canada 1986B). Heaviest snowfall usually occurs in May (when it can seriously affect light-penetration through the ice at the season of maximum ice thickness), and again in early fall during a period of failing light but relatively thin ice.

SITE DESCRIPTION

The position of our station in 1987 (74° 38' 50.7"N, 95° 01' 27.8"W; Figure 2) happened to correspond almost exactly with that of Station 31 (74° 38.4' N, 95° 01.1'W) of Prinsenberg and Bennett (1987). A site within 1-3 km of this location (Figure 2) has been occupied or used for sampling from mid-March to early July beginning in 1984, but not always over the same periods. At these stations water depth varied from 87 to 105 m. Ice and snow depth varied from year to year but were in the range of 1.5 to 2.1 and 0.1 to 0.5 m respectively, with snow depth being greatly influenced by local drifting.

METHODS

At the station, from one to three insulated, portable structures were set up (Parcoll, Panabec Manufacturing, Montreal) over a hole at least 0.75 m in diameter, previously cut in the ice to provide shelter, accommodation and laboratory space, as well as access to the water. Each shelter was supplied with at least one electrically-powered winch and such additional portable scientific equipment as required. Each Parcoll was served by a 5-7 kw diesel generator and a portable oil stove. Water samples were collected with Niskin bottles of appropriate size, or with an under-ice pumping system. In addition to plant pigments, we collected ice and water samples for analysis of ammonia, nitrate, silicate and phosphate by standard analytical methods. Particulate samples were collected from ice and water for determination of carbon, nitrogen, protein, soluble and structural carbohydrate, lipid and ATP. Zooplankton were captured with several sizes of relatively conventional nets lowered and then towed vertically over a measured distance before being closed with a throttling system, or mounted so as to fish horizontally at a given depth in the tidal stream. Net diameters ranged from 0.5 to 1.0 m in diameter and were fitted with appropriate mesh between 30 and 1,800 μm, according to the size of organisms to be sampled. Zooplankton samples were preserved in 2% neutral formalin solution or frozen after filtration to remove excess sea water. Dry weight of zooplankton was determined routinely after drying at 60°C, and frozen samples were analyzed for gut-pigment following Mackas and Bohrer (1976). Some samples were analyzed for their proximate chemical composition as in the case of the other particulate samples mentioned above.

Generally, sampling the epontic algal community was carried out with a SIPRE coring auger. When larger quantities of ice algae were required, a JIFFY ice auger (23 or 25 cm diameter) was used to core to within a few centimetres of the algal layer and the remaining ice was broken free with an ice-chisel. The algal-rich ice chips could then be collected at the surface of the auger-hole with a household strainer. Sampling was often carried out through such auger-holes with a portable winch or pump when it was important to obtain information where the under-ice distribution of light was not affected by opaque objects introduced by humans.

In most cases physiological experiments with both plants and animals were carried out in incubators in the Parcoll cooled by continuously-flowing sea water pumped from beneath the ice. For most photosynthesis, nutrient-uptake and respiration studies, algae - containing ice from SIPRE cores was melted in sea water (~10:1 sea water:ice melt volume) and incubated over a range of light intensities simulating natural conditions under the ice. Carbon-14 and nitrogen-15 were used as tracers in most photosynthesis and nutrient-uptake investigations.

Current velocities and direction were routinely determined with an Aanderaa current meter, either as part of an array mounted under the ice and anchored to the bottom or mounted separately to an aluminum pole frozen in the ice. Density-profiles were taken with a Guildline Model 8770 portable CTD. Velocity-profiles in the top 30 cm of water directly under the ice were studied with a unique profiling system developed at BIO and Dalhousie University by Dr. Terry Chriss.

For details of the methods used in our studies, see references in the next section.

OBSERVATIONS

Epontic Algae

Apparently ice algae become associated with sea ice as soon as it is formed in the fall, but the mechanism is uncertain (Horner 1985B). What we do know is that sometime about the beginning of April the bottom of the ice shows enough colour to be detectable with the unaided eye. From that time until late May, the chlorophyll concentration at the interface increases in roughly linear fashion and can exceed 200 mg Chl m^{-2}. Experimental

manipulation of the snow cover has shown that optimal light conditions (those supporting maximum chlorophyll concentrations) for the algae are found within the range of naturally-occurring snow depth. Pigment concentrations under artificially snow-free ice are substantially below the maximum and maintaining such an area clear of snow for nearly two months does not augment the pigment crop, suggesting that the ice algae are genetically shade-adapted (Cota 1985).

How is the standing crop of ice algae controlled? Smith *et al.* (in press) constructed a model of how the physical environment affects the primary production of the epontic plants. The photon-flux density (PFD) in $\mu E\ m^{-2}s^{-1}$ (I' Figure 3), striking the snow surface of the frozen ocean will be partially reflected (a). The remainder will be subjected to three separate attenuation coefficients: k_s (cm^{-1}), operating on snow depth, Z_s (cm); k_i (cm^{-1}1) operating on ice thickness, Z_i (cm); and k_{chl} (m^2mg^{-1}), the attenuation coefficient for the ice algae themselves. These coefficients determine in additive fashion the amount of light reaching the sub-ice water, $\mathbf{I}_\mu$:

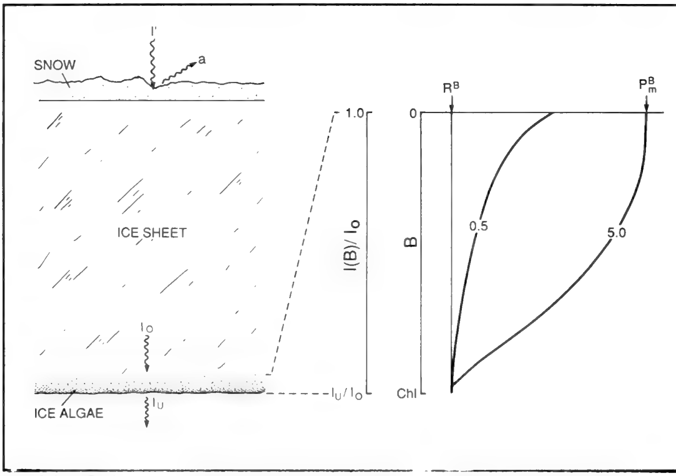

FIGURE 3: A cross-section of the annual sea-ice sheet, showing the relatively narrow zone of algal growth near the ice water interface (stippled area) and the downwelling solar radiation at the snow surface, the top of the algal layer, and at the ice water interface (**I'**, $\mathbf{I}_0$ and $\mathbf{I}_\mu$ respectively). Profiles of biomass-specific photosynthesis (thicker curves) and respiration (vertical line designated $\mathbf{R}^B$) are shown as functions of areal chlorophyll concentration, B, and the correspondingly attenuated solar radiation, I(B), through the algal layer. The photosynthesis profiles illustrate two different ratios (0.5 and 5.0) if $\mathbf{I}_0$ to the photosynthetic parameter $\mathbf{I}_K$. The remaining terms are defined and explained in the METHODS section.

$$[1] \quad \ln(\mathbf{I}_\mu/\mathbf{I'}) = -a \cdot -k_i \cdot Z_i - k_s \cdot Z_s - k_{chl} \cdot Chl.$$

The amount reaching the top of the algal layer is:

[2] $\mathbf{I_o = I' \cdot exp(-a\text{-}k_i \cdot Z_i - k_s \cdot Z_s)}$

At any level within the algal layer, the PFD reaching the cells is determined as:

[3] $\mathbf{I(B) = I_o \cdot exp(-k_{chl} \cdot B)}$, where **B**, the concentration of chlorophyll in mg m-^{2}

varies from 0 at the top to Chl at the bottom (Figure 3).

Biomass-specific photosynthetic rate ($\mathbf{P^B}$, μgC$\cdot\mu$gChl a$^{-1}\cdot$h^{-1}) as a function of PFD is often written (e.g. Lewis *et al.* 1985) as:

[4] $\mathbf{P^B = P^B m \cdot [1 - exp(I/I_k)]}$,

where $\mathbf{P^B m}$ is the light-saturated maximum in $\mathbf{P^B}$ and $\mathbf{I_k}$ is the "adaptation parameter", equivalent to $\mathbf{P^B m/\alpha}$, where α is the initial slope of the $\mathbf{P^B}$ vs **I** curve. The algal respiration rate $\mathbf{R^B}$ in μgC$\cdot\mu$gChl a$^{-1}\cdot$h^{-1} is assumed to be independent of light and a constant function of photosynthesis (Figure 3).

Also shown in Figure 3 are two theoretical curves relating photosynthetic rate at different depths in the algal layer to the ratio of the input level of illumination ($\mathbf{I_o}$) and the adaptation parameter ($\mathbf{I_k}$). Both curves are shown to attenuate to the point at which $\mathbf{R^B = P^B}$, the compensation light level $\mathbf{I_c}$. Here the chlorophyll concentration is at the light-limited maximum ($\mathbf{B_{max}}$), and net production ($\mathbf{P_{net}}$) is also maximized (Figure 4). The maximum possible integrated net production ($\mathbf{P_{opt}}$) is the integrated difference between photosynthesis and respiration when Chl = $\mathbf{B_{max}}$. Based on the foregoing relationships, $\mathbf{B_{max}}$ can be calculated as:

[5] $B_{max} = (-1/k_{chl} \cdot 1n[(-I_k/I_o)\ \mathbf{1} \cdot 1n(1-R^B/P^B m)]$.

Smith *et al.* (in press A) have used these relationships to examine their own and others' data from both the Arctic and Antarctic. The average compensation intensity ($\mathbf{I_c}$) was 0.56 μE$\cdot$m$^{-2}\cdot$s^{-1} for the Resolute data, which might also be equivalent to $\mathbf{I_{crit}}$, the intensity of light necessary to initiate ice algal growth in early spring, in which case epontic production could begin as early as the first week in March in a low-snow year (Smith *et al.*, in press

B). B_{max} values calculated for the Resolute area and from data in the literature for other arctic sites, virtually always equalled or exceeded the maximum standing crops measured in the field, and were only approached under conditions of very heavy snow and low standing crop. Hence, the model seems to provide a true upper bound, as imposed strictly by light limitation.

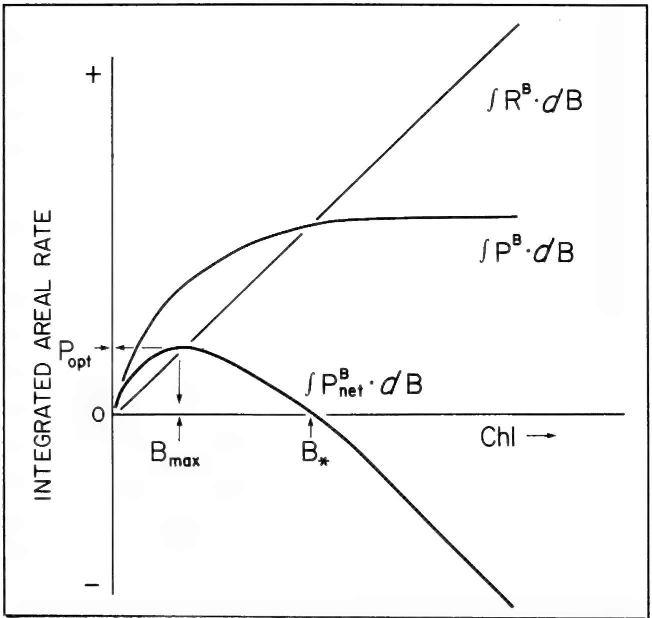

FIGURE 4: The functional relationship between vertically-integrated areal production and respiration rates ($mgC \cdot m^{-2} \cdot h^{-1}$) and integrated areal chlorophyll concentration, Chl ($mg \cdot m^{-2}$). All terms are described in the METHODS section.

While these observations are in complete agreement with the concept of light limitation as a controlling factor for ice-algal production, the fact that light parameters alone do not provide an accurate prediction of standing crops and growth rates suggests that there are others. The biomass of epontic algae, however determined, shows frequent oscillations over the spring-growth period. A probable association of such fluctuations with lunar tidal patterns has been observed several times (Figure 5a). Note also that in the Resolute area growth rate, nutrient demand and certain photosynthetic parameters also show a coupling with tidal range (Figure 5b,c). Greater allocation of recent products of photosynthesis to nitrogen-containing protein, rather than lipids and carbohydrates, was also correlated with greater tidal mixing (Smith *et al.* 1987).

Near the mouth of the Great Whale River, in Hudson Bay, strong salinity-induced stability may inhibit the vertical advection of nutrients, especially phosphate, during periods

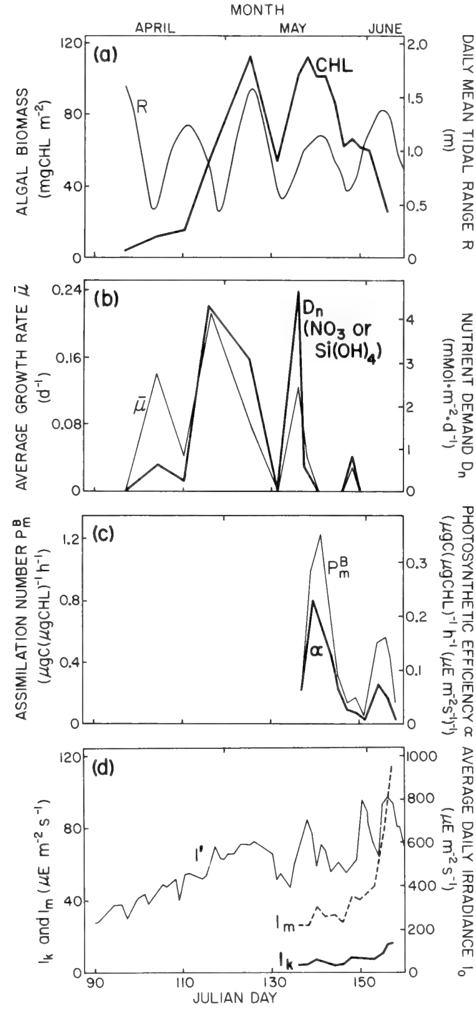

FIGURE 5: (a) The temporal development of the ice-algal bloom is shown as concentration of chlorophyll (CHL) plotted with the daily mean tidal range (R). The algae begin to slough off the ice toward the end of May. (b) Average growth rate (μ) is plotted with the estimated nutrient demand (D_n). (c) Photosynthetic performance if described by the maximum assimilation number $P^B m$) and the photosynthetic efficiency (a) is also shown for the latter part of the bloom. (d) The index of photoadaptation (I_k) and the optimal irradiance for photosynthesis (I_m) are plotted with the average daily incident irradiance (I) (from Cota and Horne 1988).

of low tidal activity. During spring tides, greater mixing and entrainment of deeper water increases the available nutrients near the ice (Gosselin *et al.* 1985).

The explanation is not so obvious near Barrow Strait where tidal currents are generally strong and nutrient profiles suggest that there should be no limitation (Figure 6). There would certainly be sufficient nitrate, phosphate and silicate to support a phytoplankton bloom if the cells were more or less uniformly suspended over a length of water column and continuously bathed in the nutrient-rich water ... provided, of course, there was sufficient light. However, the ice algae are highly concentrated and growing in a layer as on an agar plate. Hence, the availability of nutrients is not the same to the cells deeper in the ice, but nearer to the light source, and to those at the bottom of the layer. So, in addition to a light gradient (Figure 3), there is also a nutrient gradient (Figure 7).

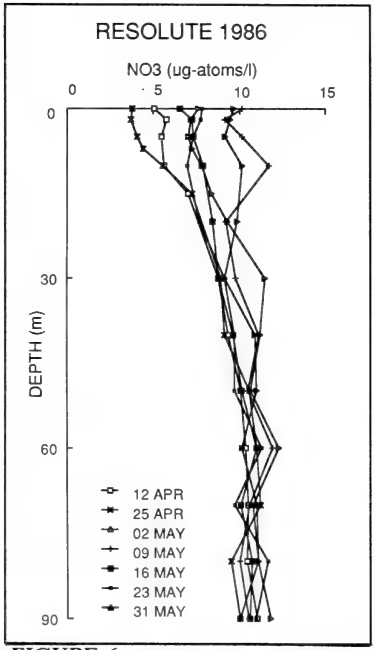

FIGURE 6: Profiles under the ice showing the vertical distribution of nitrate (NO_3) in μg-atoms l^{-1} on different dates in 1986.

Cota *et al.* (1987) have examined several mechanisms that might affect the nutrient demand along this gradient. The desalination process as ice forms results in drainage of brine through channels to the water beneath - even from the skeletal layer that supports algal growth. Some convective mixing is generated by this process, but it will be more important earlier in the season when the ice is growing rapidly. By May when the algal demands are highest, ice growth stops and hence brine-induced mixing would be minimal. Nutrient concentration parallels salinity concentration over most of the ice sheet so older ice is the most impoverished (Grainger 1977). Even if the nutrients in the entire ice sheet were available they would only support one or two weeks of rapid growth.

Regeneration within the algal layer is also potentially a mechanism wherein ammonia or other forms of organic nitrogen might become available for reuse. Using data on excretion by a variety of zooplankton, ciliates and bacteria from the literature, Cota *et al.*

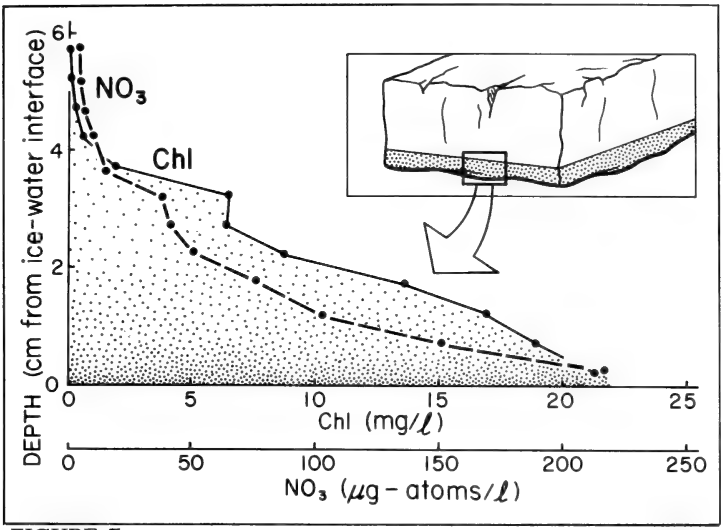

FIGURE 7: A cross-section of the annual sea-ice sheet, showing the algal-growth zone (stippled) enlarged to demonstrate the parallel distribution of nitrate (NO_3) and chlorophyll (Chl) in the bottom few centimeters of ice.

(1987) have calculated that the regenerative fluxes of ammonium-nitrogen might just meet the demand in some sub-ice environments, but the regeneration rate for silicic acid to make new diatom shells seems too low (Nelson and Gordon 1982).

So the primary source of nutrient enrichment must come from water near the epontic environment. Regardless of whether the concentrations near the ice are high or low, the important consideration is the rate of flux (i.e. renewal) across the mixed layer from the source of so-called "new" nutrients beneath the pycnocline. In their treatment, Cota *et al.* (1987) have set up a two-layer model with one gradient across the pycnocline and the second bringing material across the mixed layer to the ice. As the tidal range increases, the turbulent kinetic energy and the current shear both increase as the square of the daily range. The coefficient of vertical eddy diffusivity also varied by about an order of magnitude between the low neap tidal range and high springs. Although the fitted model does not match the data perfectly, a fortnightly pattern in the flux of both nitrate and silicic acid is demonstrable: the nutrient demands by the ice algae are easily satisfied during springs but are sometimes insufficient during neaps.

While we recognize the existence of a gradient across the algal growth layer (Figure 7), we have not yet measured the flux along it. Nonetheless, the concentrations of nitrate in the ice, though varying, are generally quite high - high enough to saturate the uptake system. Further, they can be an order of magnitude higher than in the adjacent sea water. At present, we do not know if the high concentrations, which also extend to ammonia, are in the interstitial water, and part of the ice/water complex, or perhaps are in the internal storage pools of the ice algae themselves. As shown in Figure 8, the amount and proportion of nitrate taken up (upper graph), the total amount of nitrate present (middle graph) and chlorophyll concentration in the ice (lower graph) are well correlated, which might indicate a direct association with living cells for all.

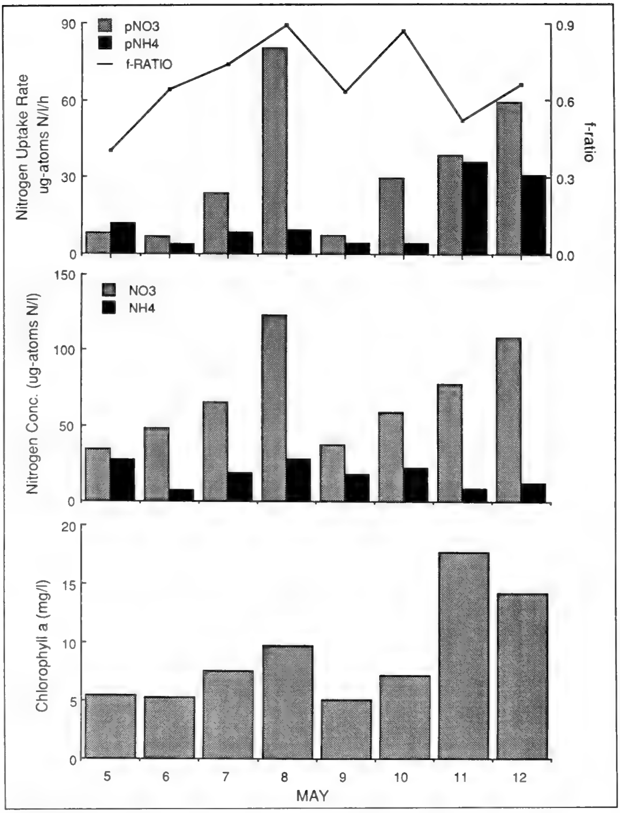

FIGURE 8: (Top) Bars give uptake rates for nitrate (pNO_3) and ammonium (pNH_4) in μg-atoms N $l^{-1}h^{-1}$ in the ice-algal layer; line shows the f-ratio, the fractionof the total nitrogen uptake supplied by nitrate. (Middle) Nitrate (NO_3) and ammonium (NH_4) concentrations in μg-atoms N l^{-1} in the ice-algal layer. (Bottom) Chlorophyll a concentration of mg l^{-1} in the ice-algal layer. All data from May 1986.

In conclusion, there seems to be a close coupling between the amount of tidal mixing and the production of epontic algae, but a precise understanding of how such physical forcing brings about the observed effects is still unclear. The case for nitrate as the limiting nutrient is weaker than before; perhaps silicic acid (G.F. Cota, unpublished data), or some

still-unmeasured micronutrient is the key.

Sub-Ice Fauna

To address the importance of under-ice primary production in the ecology of high-latitude environments, we need to understand what happens to it and how it enters into the trophic structure. There have been several accounts of the composition of the fauna associated with the epontic algae (reviewed by Carey 1985), but relatively few attempts to determine the quantity of organisms, their biomass, or to quantify their food relations. Certainly the act of sampling this diverse assemblage is formidable. For the macrofauna, the usual approach is to manually scrape the under-ice surface with a diver-operated net designed to uniformly sample a linear transect, but photographic or visual analyses must be made to evaluate escapement which is greater if the ice surface is rough (Cross 1982; Gulliksen 1984). Visual methods have verified that macrofaunal amphipods are several times more abundant on rough than on smooth ice, with greatest abundance on multiyear ice (Gulliksen and Lønne 1987). Numbers were enormously variable, depending to some degree on ice-type, and, in terms of wet-weight, ranging from zero to more than 30 g m^{-2}.

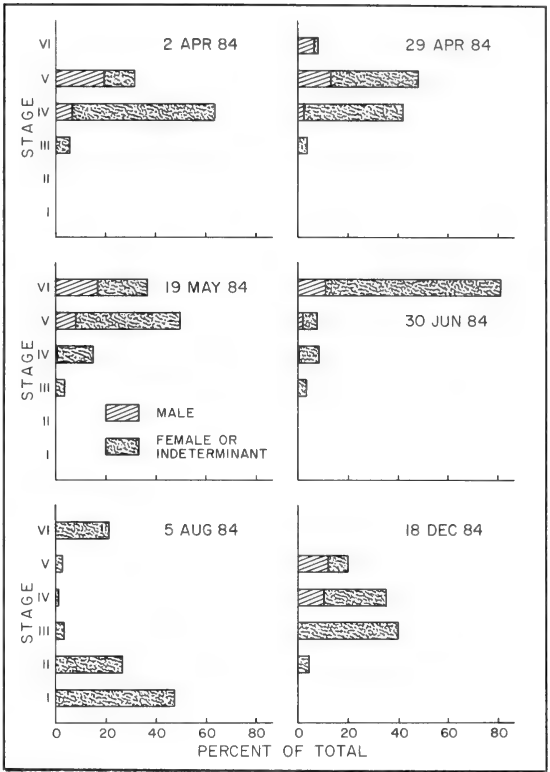

FIGURE 9: Population structure, on six dates in 1984, of the copepod, Pseudocalanus sp., shown as the percentage of the total of this species present in the water column in Resolute Passage that is contributed by each copepodid developmental stage.

Despite the overwhelming dominance of amphipods in macrofaunal collections, studies of the trophic relations at the ice edge off Pond Inlet suggested that the dominant nektonic

predator, the Arctic cod, generally ate more calanoid copepods than other prey regardless of year-class or site of capture (Bradstreet and Cross 1982). So it became another objective of our research group to establish the association, if any, between the epontic algae and the planktonic animals living in the water beneath the ice.

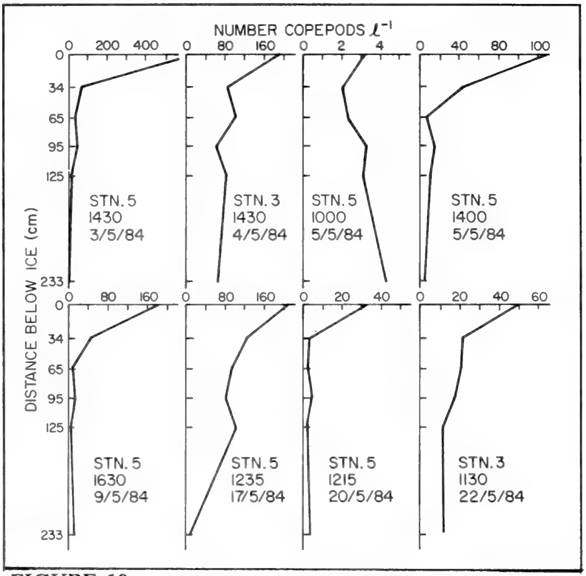

FIGURE 10: Concentration of copepods, largely Pseudocalanus sp., under the ice in the upper 2.3 m of the water column of Resolute Passage on seven dates in May 1984.

In 1984 we made a series of plankton tows, and took pump-samples during the fast-ice season, with additional tows in August and December, that showed the numerically-dominant copepod off Resolute (*Pseudocalanus* sp.) was growing and developing under the ice (Figure 9). There were virtually no sexually-mature individuals in the April 2 population, which was similar in structure to the overwintering population found the following December, but, in between, a generation matured by the end of June - well before the post-break-up bloom and its offspring developed over the "Arctic summer". We also found, using the pumping system, that at times *Pseudocalanus* as highly concentrated directly under the ice (Figure 10). Parallel feeding experiments, using algae melted from the ice, yielded rates comparable to the highest ever observed for the genus, even though our experimental temperature was 10-15°C colder than those used elsewhere (Conover *et al.* 1986). Animals could completely fill their guts 5-10 minutes after first exposure to food.

We were unable to see any clear pattern of vertical migration in 1984, but thought that there might be a relationship between "swarming" of *Pseudocalanus* near the ice and current speed. We hypothesized that the copepods, being hungry after a long winter, would seek

the under-ice surface at every opportunity and should aggregate most efficiently near the ice during periods of minimal current. On the other hand, the strongest currents would erode the maximum amount of ice algae. Hence feeding and aggregation should be concentrated near the ice somewhat before slack water during declining flows. In the absence of direct current measurement in 1984, a tidal model was constructed that seemed to fit the hypothesis reasonably well on the basis of available data (Conover *et al.* 1986).

Attempts to verify the model in subsequent years suggested that the original hypothesis was too simple (Conover *et al.*, in press). For one thing, dense concentrations of *Pseudocalanus* were rare and very transitory. Then in 1986 attempts to establish a relationship between zooplankton behaviour and current speed were complicated by a diel migratory signal. Six 32-hour sampling regimes were established, three during neap and three during spring tides, and each was accompanied by detailed current observations. In all six experiments *Pseudocalanus* appeared in greater concentrations in the upper 10 m sometime between 1900 and 2400, although the timing varied somewhat on the different dates (Figure 11). Some individuals accumulated in the upper 1 m (dashed line, Figure 11), which was generally devoid of animals at other times. At 10 to 30 m depth there was no consistent pattern (dotted line, Figure 11).

Chlorophyll concentrations under the ice did not show an interpretable pattern relative to current velocity (Figure 11), which was generally the case for all six experiments. In contrast, gut-pigment concentrations in the animals, particularly those captured in the upper 10 m, showed an evening increase that correlated well (but sometimes with a time-lag) with the peak in abundance of animals in the upper waters. Moreover, the animals in the 10-30 m layer also showed a gut-pigment peak, which in four out of six experiments roughly coincided with that in the upper water, even though there was little evidence for a comparable migration. Mention has been made already of the open water in Barrow Strait in 1986, and the higher than usual concentrations of phytoplankton before break-up, so perhaps gut-pigment levels in the zooplankton were not related to ice-algal production then.

Other zooplanktonic forms accumulated in the vicinity of the ice/water interface, although their migratory behaviour was not usually predictable. The buoyant eggs of *Calanus hyperboreus* (the dominant herbivorous copepod of the High Arctic) develop under the ice so that its nauplii are in a favoured position for further development long before the ice goes out (Figure 12). Gut-pigment analysis has confirmed that they are feeding at times,

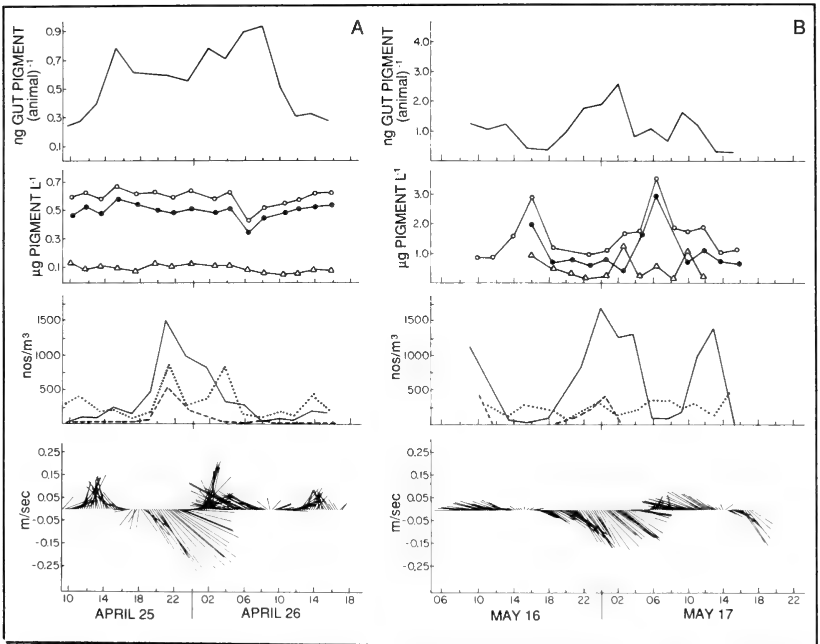

FIGURE 11: Representative diel observations for a spring (A, April 25-26, 1986) and a neap tide experiment (B, May 16-17, 1986). Bottom graph shows speed, in meters s^{-1}, and direction of tidal current with reference to the Y-axis, south being negative and north, positive. Second graph from the bottom gives numbers of Pseudocalanus sp. m^{-3} in three depth strata: (solid line) 0-10 m below ice; (dotted line) 10-30 m below ice; and (dashed line) 1 m below ice. Second graph from the top gives distribution of chlorophyll-derived pigments in $\mu g\ l^{-1}$ at 1 m below ice: (solid circles) chlorophyll a; (open triangles) pheopigments; and (open circles) total pigment. Top graph gives gut pigment in ng $(animal)^{-1}$.

but their abundance is so variable that we have been unable to see a pattern. Small copepods such as *Acartia longiremis* and *Oithona similis* occur regularly just under the ice, and, by late May, barnacle (cirripede) nauplii, the most abundant of a number of benthic invertebrate larvae, can completely dominate the samples (Figure 12).

Another large copepod, *Calanus glacialis*, seems to employ a somewhat different life-history strategy that is probably related to ice algae. In some parts of its range this species seems to require the presence of a phytoplankton bloom to induce maturation and spawning, for example, along the ice-edge in Fram Strait (Hirche and Bohrer 1987). In Resolute Passage the animals appear in the upper 30 m in mid-May and quickly mature. Because of their large size and relative scarcity, they are rarely caught with the pump so we do not know much about their movements near the ice, but they frequently contain chlorophyll-

related pigment. In the laboratory they spawn readily, regardless of whether they receive food, but they laid more eggs when fed. So at least some of their off-spring would get a head start, perhaps saving a year in the completion of their life-cycle.

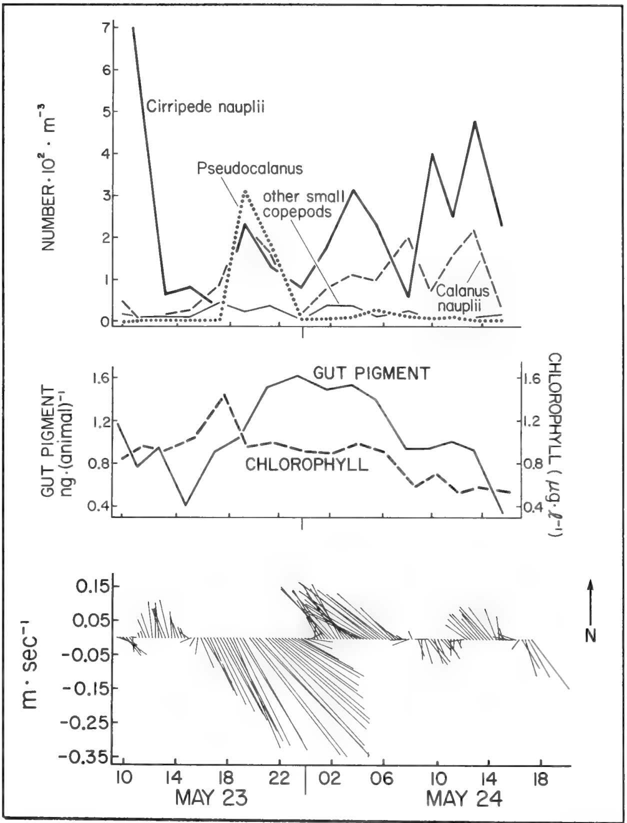

FIGURE 12: Diel observations for a spring tide experiment (May 23-24, 1986). Bottom graph shows current speed and direction (as in Figure 11). Middle graph gives gut pigment in animals (solid line) from the 10-30 m strata below ice in ng (animal)$^{-1}$ and chlorophyll a in μg l^{-1} (dashed line) at 1 m below ice. Top graph shows the number $\cdot 10^2 \cdot m^{-3}$ of Pseudocalanus (dotted line), Calanus hyperboreus nauplii (dashed line), other small copepods, predominantly Oithona and Acartia (thinner solid line), and cirripede nauplii (thicker solid line), all at 1 m below ice.

Boundary-Layer Physics

In a strong current, the liquid is turbulent and mixes rapidly, but near a surface (e.g. the under-ice surface) friction reduces mean velocity (Figure 13). As the turbulence is reduced, the water begins to act like an increasingly viscous fluid until the velocity is zero. The laws of physics argue that this process is a function of molecular viscosity, the density of the water and a stress term, from which one can calculate the thickness of the viscous boundary layer (linear velocity region).

In a controlled laboratory experiment it is easy to measure the controlling parameters and constants and predict the thickness of the viscous layer, but the natural environment can offer surprises. Using a system to actually measure the thickness of the viscous boundary

layer on the underside of the ice, developed by Dr. Terry Chriss and BIO scientists, we found that the layer was substantially thicker than a laboratory experiment predicted. So deviation from linearity (Figure 13) should have been around 0.2 cm rather than a bit less than 0.4 as measured. In other words, the stress was somehow reduced because the molecular viscosity and density of the water were constant.

We believe the algae themselves are reducing the turbulence of the environment by making the water "slipperier", probably by secreting large molecules into their surroundings. In so doing they presumably favour their own survival in increased current velocity, and perhaps in a stronger nutrient flux, without exposing themselves to increased turbulence that could erode them from the ice.

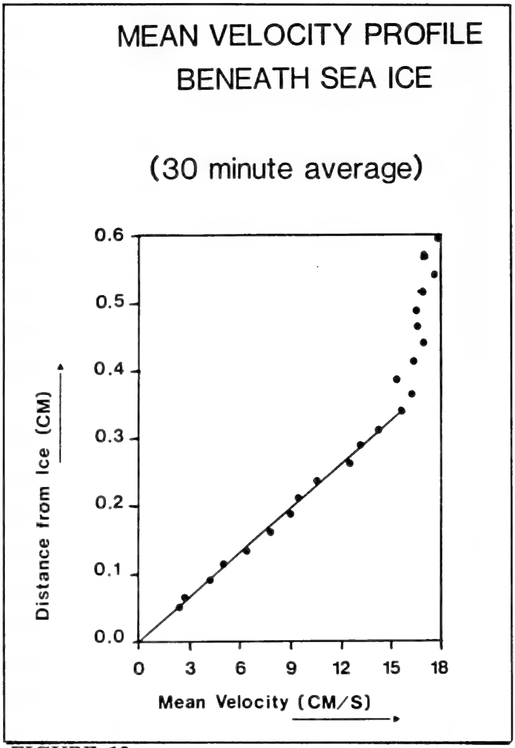

FIGURE 13: Current velocity beneath sea ice showing the viscous boundary layer (region of linear velocity). See **Boundary-Layer Physics** section for further explanation.

DISCUSSION AND FUTURE RESEARCH

How important is primary production of the ice/water interface to the total for the northern polar regions? Several years ago it was suggested that 10 g C y^{-1} m^{-2} might be a reasonable annual average for areas of one-year ice (Subba Rao and Platt 1984). Using one calculation of the area of the Arctic Ocean suitable for this kind of production (4.6%),

they found that $6 \cdot 10^6$t C y^{-1} are contributed to arctic food-chains from this source. However, their estimate could be too low because the change in area of ice-covered ocean between summer and winter can be 20-25% (Weeks 1976) or 50% (Walsh and Johnson 1979) of maximum, implying a considerably greater area of annual ice potentially suitable for epontic primary production. Subba Rao and Platt also calculated that 27 g C $y^{-1}m^{-2}$ were generated by phytoplankton where arctic waters were less than 200 m deep and 9 g C for the deeper parts of the Arctic Basin, but they apparently did not ascertain how much of the total environment was suitable for phytoplankton growth. Hence, their calculation of $206 \cdot 10^6$ t C y^{-1} of phytoplankton productivity, which makes ice-algal production a trivial 3%, is much too high.

Our observations show that very little primary production takes place in the water beneath the ice; the bloom generally occurs after, or as the ice is breaking up, therefore only about 4.6% of the Arctic Basin (the same area that supports annual ice) would generate significant phytoplankton growth. Recalculation using data supplied in Subba Rao and Platt (1984), but applied to areas that have an open-water season, gives an annual phytoplankton crop of $9.54 \cdot 10^6$ t C. Epontic production then is $6/(6 + 9.54)] \cdot 100 =$ 38% of the total 15.54, only slightly greater than $13 \cdot 10^6$ t originally calculated by Platt and Subba Rao (1975). All of this newly-estimated production takes place around the edges of the Arctic Basin, however, totally ignoring the 95.4% more or less continuously covered with ice. Using the only available data for this part of the northern ocean, that from Drift Station Alpha estimated to be 1 g C y^{-1} m^{-2} (English 1961), enables the further estimate of $12.5 \cdot 10^6$ t C additional phytoplankton production, but with no additional estimate for epontic production.

What is happening under the multiyear ice of the central Arctic Basin is perhaps beyond the scope of the Arctic Islands. Yet there are areas of multiyear ice within the archipelago, and, at the moment, we know virtually nothing about biological activity under such environments. Recent observations by Gulliksen and Lønne (1987) that macrofaunal amphipods are more important on multiyear ice than on new or first-year ice must indicate a favourable nutritional environment as well as more places to hide. While the light regime will not be so uniform as under one-year ice, the larger surface area should present a greater amount of suitable substrate per unit area of epontic algae. The test of such a hypothesis is probably best examined within the Arctic Islands to keep logistical costs down.

A recent theoretical maximum rate of photosynthesis by sea-ice algae of 1 g C $d^{-1}m^{-2}$ determined by Smith *et al.* (in press A) for low-snow environments will certainly not apply throughout the Arctic, but it suggests an annual total greater than the value of 10 g C $y^{-1}m^{-2}$ used by Subba Rao and Platt (1984). However the calculations are made, epontic production is not trivial and probably is at least 20 to 50% of the total, perhaps more within the archipelago.

Large-scale water movements, such as those generated by wind and tide, are important in the distribution of Arctic Ocean ice, thus they have considerable influence on where epontic production will occur. The physics of near-ice water motion may have equal or greater influence but we are just beginning to understand its importance. If ice algae can alter their physical environment (Figure 13), they might also regulate their nutrient supply making themselves less vulnerable to erosion and/or predation by grazers. We have explored how tidally-related mixing can introduce nutrients from below the euphotic zone to the immediate vicinity of the ice (Cota *et al.* 1987), but we still do not know precisely how the final few centimetres of algae mixed with ice (Figure 7) are nourished.

To the animals living directly in (micro- and meiofauna) or on (macrofaunal amphipods) the epontic algal layer, getting enough to eat would seem to present no problem, but quantitative information on feeding-rates is largely lacking. For the sub-ice pelagic animals, it is relatively easy to study their feeding on ice algae already removed from the ice, but we do not know if they can actually browse on attached algae as the larger Antarctic euphausiids (krill) apparently can (O'Brien 1987). If they do not graze directly on the under-ice surface, what percentage of their food is eroded by frictional shear of tidal currents (possibly modified by the algal exudates mentioned earlier), and how much simply drops off? Later in the spring as the ice begins to melt, ice algae may come off in sheets, some of which are still capable of photosynthesis and maintaining a colonial integrity, but their contribution to higher trophic levels is unclear.

What are the concentrations of zooplankton that might be at least partially dependent on epontic primary production? Figure 9 shows that *Pseudocalanus* sp. grew steadily during the pre-breakup spring in 1984. Over this period a maximum concentration under Resolute Passage ice of about 10^6 m^{-2} was recorded, equivalent to 7.66 g dry-weight. This is approximately equal in biomass to the maximum of more than 30 g wet-weight of ice-

amphipods m^{-2} mentioned by Gulliksen and Lønne (1987), assuming that the amphipods are about 75% water (Percy and Fife 1981).

Between April 1 and mid-May the biomass of *Pseudocalanus* increased by about three times and the numbers more than doubled. The daily growth-rate was about 0.07 μg dry weight $(animal)^{-1}$ d^{-1} and the daily productivity/biomass ratio (P/B) equalled 0.01. Based on 19 separate experiments we estimated a daily carbon loss in respiration of 0.07 μg $C(\mu g\ C)^{-1}$ leading to an estimate of growth efficiency K_2 of 0.13. A daily primary production rate of 0.5 gC $m^{-2}d^{-1}$, from some source, would be necessary to sustain the observed growth in zooplankton over the period. Presumably most would come from the under-ice assemblage.

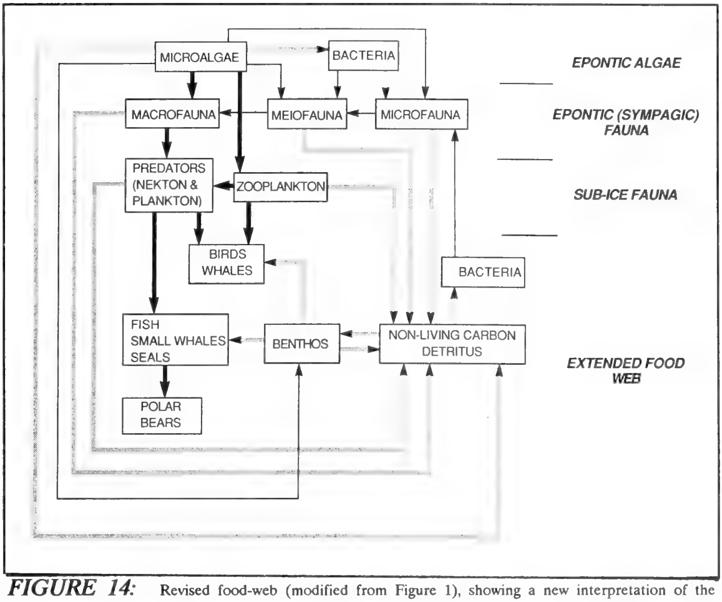

FIGURE 14: Revised food-web (modified from Figure 1), showing a new interpretation of the important trophic links between the ice biota and the remaining High Arctic communities, omitting man. Energetic linkages are similar to Figure 1: (1)heavy solid arrows = observed, including our recent observations; (2) stippled arrows = inferred from other data; and (3) thin solid arrows = hypothesized.

Such a value falls within the upper range of theoretical production by epontic primary producers recently proposed by Smith *et al.* (in press A). However, as remarked earlier, the quantity of *Pseudocalanus* was dramatically higher in 1984 than in other years. In 1985, *Pseudocalanus* populations and biomass were only 15% of the previous year, and there was

no clear increase in total biomass during spring. With no "production" and a generally lower biomass, the necessary primary production for maintenance would be only 0.03 gC $m^{-2}d^{-1}$. Both estimates of carbon for growth and maintenance are probably lower than reality, because we have made no correction for mortality among the zooplankton.

Our observations suggest that successive waves of zooplankton penetrate the pycnocline and approach the ice as spring progresses. While *Pseudocalanus* seems to be the most significant quantitatively, the young stages of both planktonic and benthic organisms benefit from this early ration. Our work implies that Carey's (1985) food-web is probably over-simplified (Figure 1). Probably epontic primary production and pelagic secondary production are coupled (e.g. Figure 14), allowing greater food-chain efficiency and an extended growing season, thus benefitting all arctic animals.

ACKNOWLEDGEMENTS

Our investigations in Barrow Strait over the past six years could only have been accomplished with the generous assistance of the Polar Continental Shelf Project, Energy Mines and Resources Canada, which we gratefully acknowledge. A number of colleagues have also contributed to the success of this program including: Leslie Harris, Jeff Spry, Jeff Anning, Pierre Clement, Alex Herman, Don Knox, Tim Siferd and Patti Hunter. We are also indebted to Dr. W. Lehn for accurate positioning of the 1987 camp. Finally, we are grateful to Dr. Buster Welch and his colleagues from the Freshwater Institute for their continued cooperation over several field seasons.

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SURFACE TOPOGRAPHY, THICKNESS AND ICE-CORE STUDIES OF MULTIYEAR LANDFAST SEA ICE AND WARD HUNT ICE SHELF, NORTHERN ELLESMERE ISLAND, N.W.T.

Martin O. Jeffries,[1] H. Roy Krause,[2] William M. Sackinger,[1] and Harold V. Serson[3]

Abstract: Surface topography, ice thickness and the physical properties of multiyear landfast sea ice (MLSI) and ice shelves, particularly Ward Hunt Ice Shelf, are considered in this paper. The MLSI and ice shelves have an undulating topography of parallel hummocks and depressions. Measurements taken from air photographs obtained in July 1984 show that the wavelength of the undulations (hummock crest to hummock crest) on MLSI has an overall mean value of 67 m, in contrast to that of the ice shelves (251 m). An order of magnitude difference also exists between the mean thickness of MLSI and the ice shelves. In view of this, a second-order polynomial relationship between mean ice thickness and mean wavelength is suggested as a rule-of-thumb to ice thickness.

The salinity and oxygen-isotope data for ice-cores drilled in Ward Hunt Ice Shelf and various MLSI locations are presented. The oxygen isotopes are used as conservative tracers to identify fresh, brackish and sea ice. The MLSI cores contain an average of 66.3% brackish ice, 33.4% sea ice and 0.3% fresh ice. We suggest that MLSI commonly grows from brackish water that persists year-round below the ice, particularly in under-ice melt-pools that are found in inverted depressions on the bottom of the ice. West Ward Hunt Ice shelf contains a thick body of sea ice (as much as 35 m), in contrast to the east ice shelf, which is almost entirely fresh ice. We believe this is related to bottom accretion of sea ice and fresh ice associated with the flow of seawater into Disraeli Fiord, and the outflow of stratified seawater-freshwater from the fiord.

The growth of thick sea ice is discussed with reference to thermodynamic and double-diffusion models. We conclude that there is a need for field-data collection and modelling of the heat and mass-balance of thick sea ice. This is in addition to further studies of the physical-structural properties of this thick ice, particularly brackish ice, for which few data are available.

Résumé: Cette présentation traite de la topographie, de l'épaisseur et des propriétés physiques de la glace de mer côtière pluri-annuelle (GMCP) et des plates-formes de glace, en particulier la plate-forme de glace de Ward Hunt. La GMCP et les plates-formes ont une topographie ondulée en hummocks et dépressions parallèles. Les mesures tirées de photographies aériennes prises en juillet 1984 montrent que la longueur d'onde des ondulations (de crête à crête) sur la GMCP a une valeur globale moyenne de 67 m, alors qu'elle est d'environ 251 m pour les plates-formes. Il y a aussi une différence d'un ordre de grandeur entre l'épaisseur moyenne de la GMCP et celle des plates-formes. Par conséquent, on pense à une relation polynômiale de second-ordre entre l'épaisseur de glace moyenne et la longueur d'onde moyenne, comme règle empirique pour l'épaisseur de la glace.

On présentera la salinité et les données obtenues par isotopes de l'oxygène pour des carottes de glace prélevées dans la plate-forme de Ward Hunt et en divers endroits de la GMCP. Les isotopes de l'oxygène sont utilisés comme traceurs pour identifier les glaces d'eau douce, d'eau saumâtre et d'eau salées. Les carottes de GMCP contiennent en moyenne 66.3 % de glace d'eau saumâtre, 33.4 % de glace d'eau de mer et 0.3 % de glace d'eau douce. On avance l'hypothèse que la GMCP se forme habituellement à partir de l'eau saumâtre qui persiste toute l'année sous la glace, en particulier dans les mares de fonte qui se trouvent dans les dépressions inversées de la surface inférieure de la glace. L'ouest de la plate-forme de Ward Hunt se compose d'une épaisse couche de glace de mer (jusqu'à 35 m), alors l'est est presque uniquement en glace d'eau douce. Cela nous semble lié à l'accrétion par le fond de glace de mer dans le fjord Disraeli, et à la sortie du fjord d'eau de mer et d'eau douce stratifiées.

On envisagera le croissance de la glace de mer épaisse en référence aux modèles thermodynamique et de double diffusion. En conclusion, on souligne le besoin de recueillir et modéliser les données de terrain sur les bilans thermique et massique de la glace de mer épaisse, ceci en plus d'études ultérieures sur les propriétés physico-structurelles de cette glace épaisse, en particulier de la glace d'eau saumâtre, sur laquelle on a peu de données.

INTRODUCTION

The fast-ice fringe along the north coast of Ellesmere Island consists of ice shelves and multiyear landfast sea ice (MLSI). The ice shelves, particularly Ward Hunt Ice Shelf, have been the subject of occasional, intense study since the early 1950s when it was confirmed

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that the ice shelves were the source of ice islands (Koenig *et al.* 1952; see also Ommanney 1982A,B for extensive bibliographies of Arctic ice-shelf and ice-island research prior to 1982). On the other hand, unlike the ice shelves and ice islands, there has been very little research on the MLSI.

The ice shelves owe their origin to two primary processes: (1) the flow of glacier tongues into fiords and inlets, e.g. Milne Ice Shelf (Jeffries 1986); and (2) the in situ growth of landfast sea ice, e.g. Ward Hunt Ice Shelf (Lyons and Leavitt 1961; Lyons *et al.* 1971; Jeffries and Krouse 1984; Jeffries *et al.* 1988A). Much of the present landfast sea ice has grown to replace large areas of shelf ice lost by ice-island calving. In places, the landfast sea ice occupies the entire area of a bay, e.g. Yelverton Bay, or it is found attached to the front of ice shelves, e.g. Ward Hunt Ice Shelf and Milne Ice Shelf (Lyons and Ragle 1962; Lister 1962; Jeffries and Serson 1986; Jeffries *et al.* 1987, 1988B).

The growth of MLSI is a means by which the ice shelves regenerate and increase their lateral extent. Furthermore, present day MLSI growth might be analogous to the early growth of some Arctic ice shelves. Thus, studies of MLSI could lead to an understanding of the cycle of ice-shelf growth and disintegration, and of ice-shelf growth-history and processes. With the exception of the Markham Bay Re-entrant (Lyons and Ragle 1962; Ragle *et al.* 1964) and the Nansen Ice Plug (Serson 1972), there have been neither recent nor extensive studies of MLSI.

In spring 1982, an ice-coring program was begun on Ward Hunt Ice Shelf and adjacent areas of MLSI on the north coast of Ellesmere Island. The primary aim was to examine ice stratigraphy, with particular emphasis on salinity measurements and stable-isotope tracing, as well as interpretation of ice-growth processes and history. Detailed aspects of this work, including the field and laboratory methods have been published elsewhere (Jeffries and Krouse 1984, 1988; Jeffries *et al.* 1988A,B). This paper is both a summary of results obtained to date, and a presentation of new data on surface topography and ice thickness, and a new approach to the identification of fresh, brackish and sea ice in Ward Hunt Ice Shelf and MLSI. The results are discussed with reference to ice-growth processes associated with the flow of fresh, brackish and seawater below the ice.

FIGURE 1: Surface topography of multiyear landfast sea ice (MLSI) and ice shelves: Ward Hunt Ice Shelf (A); Milne Ice Shelf and Milne Re-entrant (B); Ayles Ice Shelf (C).

SURFACE TOPOGRAPHY AND ICE THICKNESS

The ice islands that were discovered in the late 1940s and early 1950s were distinguished not only by their immense size, but also by their striking undulating surface of parallel ridges and troughs (Koenig *et al.* 1952). Commonly referred to as "rolls" (Hattersley-Smith 1957), the ridges and troughs are also an ice-shelf feature, and it was this common link that confirmed that the ice shelves were the source of ice islands (Koenig *et al.* 1952).

The rolls are most easily observed in summer when the troughs contain long, linear lakes of meltwater (Figure 1). It is also clear from Figure 1 that the MLSI has a similar undulating topography, albeit at a smaller scale than the ice shelves. The term "ridge" is somewhat ambiguous when used with reference to sea ice; thus, we prefer hummock and depression for ridge and trough respectively.

There have been no systematic studies of the origin or the perpetuation of the rolls, and it is not our purpose to discuss this. Instead, new data are presented with regard to the size of the undulations and their possible relationship to ice thickness.

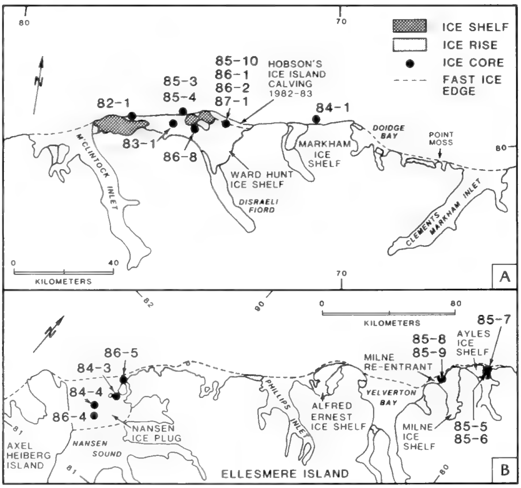

FIGURE 2: Location map of the study area and ice core locations from M'Clintock Inlet to Clements Markham Inlet (A), and Nansen Sound to Ayles Fiord (B).

Surface-Topography Variations

In July 1984, we undertook an aerial photographic survey of the ice shelves and landfast sea ice from Point Moss to Yelverton Bay (Figure 2). The wavelength of the undulations (distance from hummock crest to hummock crest) was measured at five different MLSI locations to an accuracy of 5 m. The wavelength of undulations on Markham Bay Re-entrant was measured from a 1961 air photograph to an accuracy of 15 m. On the ice shelves, single locations were

chosen on Ayles Ice Shelf and Milne Ice Shelf, as well as four different locations on Ward Hunt Ice Shelf.

The measurement data are summarized in Table 1. There is an order of magnitude difference between the overall mean wavelength on MLSI and on the ice shelves. Also, there is a greater variability on the ice shelves than on the MLSI.

There is a limited amount of relative-relief data, i.e., the vertical distance from hummock crest to depression bottom. Data from our observations and measurements are given in Table 2. In addition to actual measurements taken at three ice-core sites on MLSI, our experience in traveling over MLSI by snowmobile indicates that MLSI has a very low relative relief compared to the ice shelves.

Ice Thickness and Bottom Topography

Ground observations and air-photograph analysis indicate that large areas of MLSI are undeformed, largely due to growth in sheltered locations where pack-ice motion is minimized (Figures 1B,C) (Jeffries *et al.* 1987, 1988B). At these locations the ice has a gentle, undulating topography. At more exposed locations, e.g. the front of West Ward Hunt Ice Shelf (cores 85-3 and 85-4, Figures 1A, 2A), the ice is commonly deformed, with a rough, hummocky topography of old, weathered pressure ridges.

The mechanical deformation of pack ice results in considerable thicknesses (>5 m). In contrast, the equilibrium-thickness of undeformed multiyear pack-ice floes is 2.5-5 m (Maykut and Untersteiner 1971). Data from undeformed MLSI (except that at the front of Ward Hunt Ice Shelf) ice-cores and boreholes drilled through MLSI (Table 2) suggests that the ice thickness at least equals, and commonly exceeds the equilibrium thickness of multiyear pack ice. A more extensive ice-thickness measurement program is required to confirm this.

In addition to the unusual ice-surface topography, Jeffries *et al.* (1988B) present evidence that deformed and undeformed MLSI has a pronounced bottom topography which mirrors the surface topography. For example, at the sites of ice cores 85-3 and 85-4 (Ward Hunt MLSI), 85-5 and 85-6 (Ayles MLSI) and 85-8 and 85-9 (Milne Re-entrant) (Figure 2), allowing for the relative surface relief (Table 2), the bottom of the hummock ice is 0.85 m, 1.865 m and 1.74 m, respectively, deeper than the bottom of adjacent depression ice. These data are from single locations on each MLSI sheet and it remains to be determined

TABLE 1: MEASUREMENTS OF THE WAVELENGTH (m) OF THE UNDULATING SURFACE TOPOGRAPHY OF MLSI AND SHELF ICE.

LOCATION	MINIMUM	MAXIMUM	MEAN (± 1S.D.)	NUMBER OF MEASURE-MENTS
		MLSI		
Doidge Bay	27	70	43±8	85
Ward Hunt Ice Shelf	25	105	55±15	63
Ayles Fiord	45	121	79±17	138
Milne Re-entrant	40	127	80±21	128
Yelverton Bay	30	85	59±10	130
Markham Bay[1] Re-entrant	40	120	71±16	89
		OVERALL	67±15	633
		SHELF ICE		
Ward Hunt Ice Shelf East	87	355	212±42	84
Ward Hunt Ice Shelf South	110	398	225±69	111
Ward Hunt Ice Shelf West	110	382	258±64	101
Ward Hunt Ice Shelf External West	138	440	280±53	66
Ayles Ice Shelf	108	311	211±48	80
Outer Milne Ice Shelf	135	450	330±62	86
Ice Island T-3[2]	230	260	245	-
		OVERALL	51±57[3]	528

[1] Markham Bay Re-entrant formed at the east end of Ward Hunt Ice Shelf prior to 1962-63. The wavelength measurements were made on a 1960 air photograph.

[2] Data for T-3 are from Crary (1960).

[3] Overall mean excludes the T-3 data.

TABLE 2: DATA ON RELATIVE SURFACE RELIEF AND ICE THICKNESS OF MLSI AND SHELF ICE.

LOCATION	RELATIVE RELIEF (m)	ICE THICKNESS (m)	SOURCE
Ice core 84-1	N/A	3.77 Hummock (H)	Ice core
Ice core 85-3	1.53	7.62 Depression (D)	Ice core
Ice core 85-4		10.00 (H)	Ice core
Ice core 85-5	0.545	4.22 (D)	Ice core
Ice core 85-6		6.63 (H)	Ice core
Ice core 85-7	N/A	6.26 (D)	Ice core
Ice core 85-8	0.82	9.80 (H)	Ice core
Ice core 85-9		7.24 (D)	Ice core
Ice core 84-3	N/A	2.24	Ice core
Ice core 84-4	N/A	3.75	Ice core
Ice core 86-4	N/A	5.53	Ice core
Ice core 86-5	0.70 m	3.06 (D)	Ice core
M'Clintock Inlet	N/A	7.92	Borehole[1]
Yelverton Bay	N/A	6.50 (mean)	Boreholes (>200)
Markham Bay Re-entrant		11.00	Boreholes (Lyons and (Ragle 1962)
Ward Hunt Ice Shelf (1)	2-7.5 m	42.50[2] (mean)	Boreholes[1]
Ward Hunt Ice Shelf (2)		47.00	Ice core, Lyons *et al.* (1971)
Ward Hunt Ice Shelf (3)		44.75	Ice core 83-1, ice temperature
Ward Hunt Ice Shelf (4)		50.66	Ice core 82-1, ice temperature
Outer Milne Ice Shelf	5-7.5 m	75.00 (mean)	Radio-echo, Narod *et al.* (in press)
Ice Island T-3	N/A	48.00 (mean)	Seismic Crary (1958)

1 Personal communication, R. Verrall, Defence Research Establishment Pacific.
2 Thickness data for East Ward Hunt Ice Shelf is actually from Hobson's Ice Island, which calved from the eastern ice shelf in 1982-1983 (Jeffries and Serson 1983).
(1) to (4) See Table 1.

whether the inverted bottom-side depressions are, like their surface counterparts, long and linear features.

Hattersley-Smith (1957) proposed that the surface topography of the ice shelves was also mirrored by an inverted topography at the undersurface. Recently, however, airborne radio-echo sounding of Outer Milne Ice Shelf, where the surface depressions are particularly deep (Table 2), has shown that the surface topography has little or no bottom-side expression (Narod *et al.*, in press).

Radio-echo sounding of ice thickness has been used successfully on Milne Ice Shelf and East Ward Hunt Ice Shelf. Outer Milne Ice Shelf has a mean thickness of 75 m, and East Ward Hunt Ice Shelf a thickness of 45-50 m (Narod *et al.*, in press). The latter thickness is corroborated quite well by Hobson's Ice Island, which calved from East Ward Hunt Ice Shelf (Figure 2A) (Jeffries and Serson 1983), and has a mean thickness of 42.5 m (Table 2). Radio-echo sounding of the remainder of Ward Hunt Ice Shelf has had mixed success, largely due to the presence of saline ice (Figure 8) (Hattersley-Smith *et al.* 1969; Narod *et al.*, in press). Spot-depths for West Ward Hunt Ice Shelf have been calculated from ice-temperature profiles at the site of ice cores 82-1 and 83-1 that were drilled for this study (Figure 2A; Table 2). Lyons *et al.* (1971) drilled a 47 m ice core through the ice shelf 5 km southwest of Ward Hunt Island (Figure 2A, Table 2).

Relationship between Ice Thickness and Surface Topography

The data show that there is an order of magnitude difference between the thickness of the ice shelves and MLSI, and also between the wavelength of the undulations on each type of ice. Does this, then, suggest a relationship between ice thickness and surface topography geometry? The data were analyzed and the best relationship was found to be a second-order polynomial between mean ice thickness and mean wavelength (Figure 3). For MLSI, the mean ice-thickness data for Milne Re-entrant,

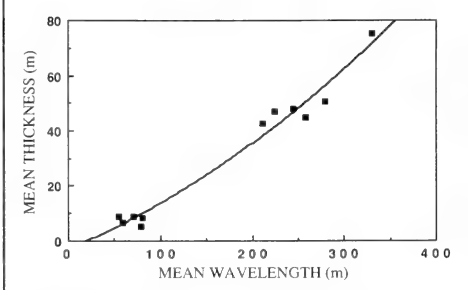

FIGURE 3: Second-order polynomial relationship between ice thickness and mean wavelength of surface undulations of MLSI and ice shelves. The line is represented by the equation $y=0.1392X + 0.0002826X^2 - 2.805$m (y:mean thickness. X:mean wavelength).

Ayles Fiord and the ice at the front of Ward Hunt Ice Shelf were taken as the mean of the thickness of adjacent hummocks and depressions, while the spot-depth for Markham Bay Re-entrant was taken as the mean thickness (Table 2). Likewise, the spot-depths for West and South Ward Hunt Ice Shelf (Table 2) were assumed to be the mean thickness.

This relationship (Figure 3) remains to be proven and would require an extensive ice-thickness measurement program. However, in view of the difficulties associated with radio-echo sounding and the probably high cost of a ground-based borehole drilling program, the relationship based on the available data might serve as a useful rule-of-thumb for the approximate determination of ice thickness. Thus, in the case of Doidge Bay MLSI and Ayles Ice Shelf (for which ice-thickness data are unavailable), the mean wavelength of the surface undulations (Table 1) indicates a mean ice thickness of 3.7 m and 39.1 m, respectively. It is interesting to note that observations made by one of us (H.V.S.) in May 1969 in Doidge Bay indicated an ice thickness of about 4 m, close to the 3.7 m derived according to the mean wavelength of the undulations.

SALINITY AND OXYGEN-18 CONTENT OF WARD HUNT ICE SHELF AND MLSI ICE CORES

The physical and structural properties of ice are primarily a function of the water properties at the time of ice growth, and not diagenetic (post-growth) processes. For freshwater ice and sea ice the physical and structural properties have been studied extensively and are, therefore, quite well known. In contrast, the physical and structural properties of brackish ice have received very little attention; hence, it is difficult to recognize brackish ice on the basis of ice structure alone. Using salinity and stable-isotope data, brackish ice was identified in Ward Hunt Ice Shelf, near Ward Hunt Island (Lyons *et al.* 1971). With this in mind, salinity and stable-isotope measurements were made on our ice cores from Ward Hunt Ice Shelf and the MLSI. In this section, the principles behind the application of stable isotopes to the recognition of fresh, brackish and sea ice are described. Then, the results are presented and discussed.

Oxygen-18 as a Conservative Tracer for Sea-Ice Studies

The loss of brine from sea ice at the time of growth and during subsequent aging means that ice salinity is not a conservative tracer for the purpose of identifying fresh, brackish and sea ice. On the other hand, the stable isotopes of ice/water are conservative tracers, since the stable isotope content of the ice remains almost the same as that of the water. Experimental studies of oxygen-isotope fractionation during freezing show that the fractionation factor (α) has a maximum value of 1.003 (O'Neil 1968). That is, during freezing the ice is enriched in ^{18}O by as much as $3^{o}/oo$ relative to the water. This is a small fractionation compared to the brine-loss from sea ice.

For the purpose of simplicity, an α-value of 1.003 is assumed for this study. Thus, after subtracting $3^{o}/oo$ from a given ice δ value, the δ value of the parent water is obtained. Jeffries and Krouse (1988) suggest that meltwater infiltration at the surface of MLSI is minimal. For the purpose of this study, δ values from the uppermost 0.5 m of ice are excluded to allow for possible infiltration of ^{18}O-depleted meltwater and alteration of original δ values, and the exclusion of refrozen melt-pools.

To obtain the water salinity from the ice/water $\delta^{18}O$ values it is necessary to know the salinity - $\delta^{18}O$ relationship in the parent water. In Disraeli Fiord and Milne Fiord, where freshwater-seawater stratification exists, owing to the damming action of Ward Hunt Ice Shelf and Milne Glacier (Figure 2B) (Keys 1978; Jeffries 1985), salinity and $\delta^{18}O$ are related as follows:

$$[1] \quad \text{Salinity} = 1.17\ \delta^{18}O + 34.51^{o}/oo$$

Assuming that this relationship applies to the entire study area (Figure 2), then, the water $\delta^{18}O$ value (derived from the ice $\delta^{18}O$ value as explained in the previous paragraph) can be used in equation [1] to determine the water salinity that prevailed at the time of growth.

Having determined the water salinity and ^{18}O content, there remains the question of what criteria to use to differentiate between fresh, brackish and seawater. In this region the freshwater is derived mainly from glacier and snow-fed rivers and streams flowing into fiords and inlets. The salinity of the river and streamwater has not been measured directly, but "freshwater" at the surface of Disraeli and Milne fiords has a salinity of $1.07^{o}/oo$ and $0.13^{o}/oo$ respectively (Jeffries 1985). These data agree with Mason and Moore (1982), who

note that river-water salinity rarely exceeds 1.0°/oo. For this study, the upper limit of the freshwater salinity is taken as 1.0°/oo.

The lower limit of the seawater salinity is assumed to be 24.7°/oo based on the knowledge that freezing kinetics and ice-growth processes change at salinities exceeding 24.7°/oo (Weeks and Ackley 1982). Table 3 summarizes the freshwater, brackish water and seawater categories according to the range of water salinity and $\delta^{18}O$ values, and ice $\delta^{18}O$ values. On this basis it is now possible to identify fresh, brackish and sea ice directly from the ice $\delta^{18}O$ values.

TABLE 3: FRESH, BRACKISH AND SEA WATER/ICE CLASSIFICATION ACCORDING TO WATER SALINITY AND $\delta^{18}O$ VALUES, AND ICE $\delta^{18}O$ VALUES.

WATER/ICE TYPE	WATER SALINITY (°/oo)	WATER $\delta^{18}O$ (°/oo)	ICE $\delta^{18}O$ (°/oo)
Sea	≥ 24.7	≥ 8.5	≥ 5.5
Brackish	1.01 to 24.69	-28.6 to -8.5	-25.6 to -5.5
Fresh	≤ 1.00	≤ -28.7	≤ -25.7

Before presenting the results, a short explanation of the ^{18}O content of seawater and sea ice is warranted. On a global basis, seawater has a mean $\delta^{18}O$ value of ~0.0°/oo (Craig 1961), with some slightly negative deviations arising from local input of meteoric water (meteoric water is water that has been involved in recent atmospheric circulation and has a $\delta^{18}O$ value less than zero). In the Arctic Ocean, where meteoric water $\delta^{18}O$ values are very negative, the surface waters have a $\delta^{18}O$ range of -4.5°/oo to +0.3°/oo (Vetshteyn *et al.* 1974; Östlund and Hut 1984), due to mixing of meteoric water and seawater. Assuming maximum isotopic fractionation on freezing, the aforementioned values correspond to ice $\delta^{18}O$ values of -1.5°/oo to +3.3°/oo. Values similar to these are found in MLSI. But, as we will show, many ice $\delta^{18}O$ values in MLSI are much more negative, and in some instances are close to the mean $\delta^{18}O$ value (-31.3°/oo) of precipitation in this region (Jeffries and Krouse 1987).

Fresh, Brackish and Sea Ice in MLSI

Twelve ice cores have been drilled in MLSI at a number of different locations throughout the study area (Figure 2). In many cases the ice cores were drilled in recognizable hummocks and depressions but, because of the snow-covered, low relative relief, it was not always possible to identify the topographic locations. The salinity and isotope data for each core are summarized in Table 4. It is noted that $\delta^{18}O$ range includes values close to $0.0^{o}/oo$, indicative of seawater, and very negative $\delta^{18}O$ values which indicate a considerable meteoric water input to the water-ice system. The mean $\delta^{18}O$ values all fall in the brackish ice range, with two exceptions (ice cores 84-4 and 86-4).

TABLE 4: SUMMARY OF ICE SALINITY AND ICE $\delta^{18}O$ VALUES IN MLSI.

ICE CORE[1]	SALINITY RANGE ($^{o}/oo$)	MEAN SALINITY ($^{o}/oo$)[2]	$\delta^{18}O$ RANGE ($^{o}/oo$)	MEAN $\delta^{18}O$ ($^{o}/oo$)[2]
84-1 (H)	0.01 to 2.09	0.85 ± 0.41	-23.8 to -2.9	-14.0 ± 6.8
84-3	0.01 to 1.93	0.37 ± 0.33	-16.4 to -9.6	-12.9 ± 1.8
84-4	0.01 to 3.41	0.74 ± 0.46	-10.9 to +0.7	-3.9 ± 3.3
85-3 (D)	0.18 to 4.39	1.26 ± 0.45	-24.5 to -0.7	-10.9 ± 8.3
85-4 (H)	0.03 to 12.06	2.92 ± 1.54	-20.7 to -1.4	-5.2 ± 4.3
85-5 (D)	0.01 to 0.22	0.08 ± 0.06	-22.4 to -13.8	-18.2 ± 2.9
85-6 (H)	0.01 to 3.84	0.60 ± 0.58	-22.9 to -1.4	-15.2 ± 7.7
85-7 (D)	0.01 to 3.53	1.21 ± 0.73	-29.9 to -1.6	-17.3 ± 6.3
85-8 (H)	0.03 to 4.54	1.61 ± 0.97	-22.7 to -2.8	-9.5 ± 5.6
85-9 (D)	0.03 to 3.30	1.07 ± 0.73	-22.0 to -6.3	-13.8 ± 5.1
86-4	0.16 to 2.49	0.74 ± 0.46	-11.0 to +0.2	-2.9 ± 3.2
86-5 (D)	0.22 to 8.87	1.50 ± 1.52	-19.0 to -2.7	-9.6 ± 4.5

[1] H and D denote hummock and depression respectively.
[2] Mean values are expressed with ±1 Standard Deviation.

The amount of fresh, brackish and sea ice in each MLSI core is shown in Figure 4. On the basis of these 12 ice cores, MLSI has an overall composition of 66.3% brackish ice,

33.4% sea ice, and 0.3% fresh ice. However, there is some variation from location to location. Some particular features are:

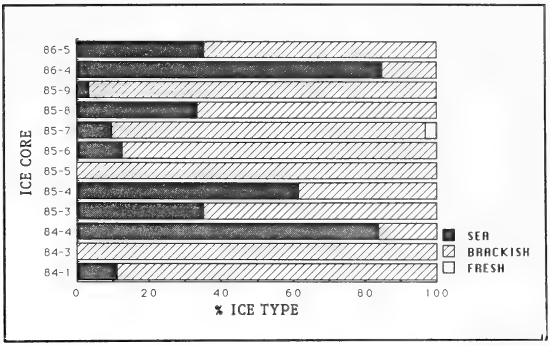

FIGURE 4: Percentages of fresh, brackish and sea ice in MLSI cores according to ice $\delta^{18}O$ values.

(1) Where the ice cores have been drilled in adjacent hummocks and depressions, the depression ice cores contain a greater proportion of brackish ice (Figure 4; ice cores 85-3, 85-4, 85-5, 85-6, 85-8 and 85-9). In consequence, depression ice has a lower salinity and ^{18}O content than hummock ice (Table 4).

(2) Two ice cores (84-3 and 85-5) are composed entirely of brackish ice (Figure 5).

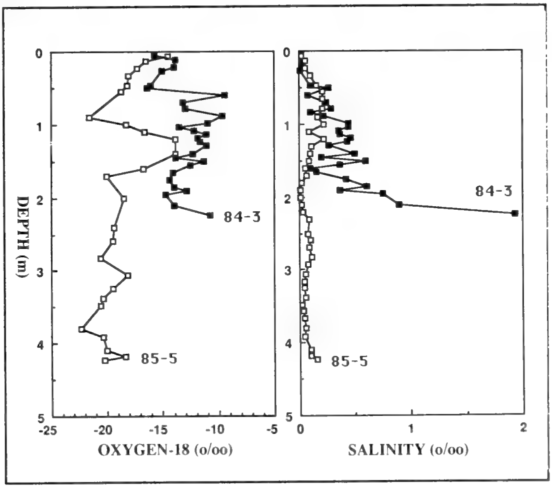

FIGURE 5: Oxygen-18 and salinity profiles in brackish ice cores 84-3 and 85-5.

(3) Not one ice core is composed entirely of sea ice, and we note that the two ice cores with the greatest proportion of sea ice are both in the Nansen Ice Plug (84-4, 86-4; Figure 2B).

(4) Deformed MLSI at the front of Ward Hunt Ice Shelf (Figure 2A) contains the most saline ice, but brackish ice also occurs here; at the bottom of the hummock and throughout almost the entire thickness of the depression (Figure 6).

Fresh, Brackish and Sea Ice in Ward Hunt Ice Shelf

West Ward Hunt Ice Shelf

The data for West Ward Hunt Shelf are from four ice cores (Figure 2A). Ice cores 82-6 and 83-9 were drilled at the crests of hummocks in a surface exposure of basement ice mapped by Lyons *et al.* (1971). Basement ice is ice that has accreted at the base of the ice shelf. Ice core 86-8 was drilled at the bottom of a depression in the region southwest of Ward Hunt Island (Figure 2A), where brackish ice was identified by Lyons *et al.* (1971). Ice core 83-1 was drilled at the crest of a hummock, about 9 km west of Ward Hunt Island.

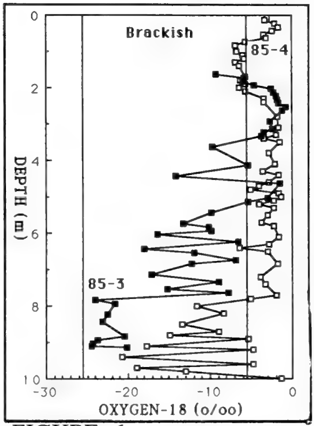

FIGURE 6: Oxygen-18 profiles in hummock (85-4) and depression (85-3) ice cores, MLSI at the front of Ward Hunt Ice Shelf. Note that in each core there is a sharp decrease in $\delta^{18}O$ values at a depth of 7.9 m.

The salinity and isotope data for each of the four ice cores are summarized in Table 5, and the amounts of fresh, brackish and sea ice in each core are shown in Figure 7. Ice cores 82-6 and 83-9 are composed entirely of sea ice. Ice core 83-1 is composed almost entirely of sea ice, with small, almost equal amounts of fresh and brackish ice. Ice core 86-8 is composed almost entirely of brackish ice; the amounts of each ice-type in core 86-8 are similar to MLSI (Figure 4).

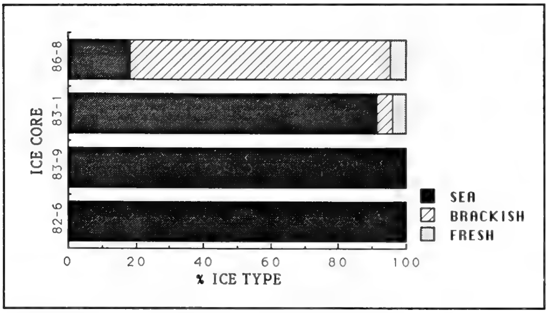

FIGURE 7: Percentage of fresh, brackish and sea ice in ice cores from West Ward Hunt Ice Shelf.

Ice core 83-1 is the longest of the four ice cores drilled in West Ward Hunt Ice Shelf, but it was not drilled right through the ice. Salinity and $\delta^{18}O$ profiles show that there are four distinct strata at this location (Figure 8). Stratum 1 is not considered here as it is the product of surface accumulation of snow and ice, not of bottom accretion. Strata 2 and 4 (Figure 8) are

TABLE 5: SUMMARY OF ICE SALINITY AND ICE $\delta^{18}O$ VALUES IN WEST WARD HUNT ICE SHELF ICE CORES.

ICE CORE	SALINITY RANGE (^{o}/oo)	MEAN SALINITY (^{o}/oo)	$\delta^{18}O$ RANGE (^{o}/oo)	MEAN $\delta^{18}O$ (^{o}/oo)
82-6 (3.49 m)	0.80 to 3.44	2.13 ± 0.51	-0.9 to +0.7	-0.14 ± 0.5
83-9 (2.06 m)	1.98 to 3.40	2.61 ± 0.45	-1.0 to +0.9	0.0 ± 0.6
86-8 (10.28 m)	0.03 to 2.14	0.70 ± 0.68	-26.6 to -0.4[1]	-14.2 ± 8.2
83-1 (31.79 m)				
Stratum 2	0.28 to 3.68	2.12 ± 0.61	-2.3 to 0.5	-1.1 ± 0.5
Stratum 3	0.04 to 0.39	0.18 ± 0.11	-26.6 to -22.1	25.5 ± 1.6
Stratum 4A	1.20 to 3.89	2.30 ± 0.62	-2.1 to 0.0	-1.3 ± 0.4
Stratum 4B	2.03 to 11.34	8.22 ± 3.81	-1.7 to 0.7	-0.5 ± 0.8

[1] Lyons et al. (1971) published three salinity -$\delta^{18}O$ values for brackish ice (0.32^o/oo and -21.6^o/oo, 0.37^o/oo and -13.2^o/oo, 0.26^o/oo and -17.5^o/oo). These values fall well within the range of values found in ice core 86-8.

sea-ice layers, as shown by the $\delta^{18}O$ and salinity values (Table 5). The salinity and $\delta^{18}O$ values of ice cores 82-6 and 83-9 are similar to those of Strata 2 and 4, and all this ice is classified as 'saline basement ice' (Jeffries *et al.* 1988A).

On the basis of ice salinity, Stratum 4 has been divided, with Stratum 4B being more saline than Stratum 4A (Table 5). Sixty-eight hours after drilling had ceased at a depth of 31.79 m, brine had upwelled in the borehole to a level of 25.63 m. This suggests considerable brine movement at these depths and the high ice-salinities in Stratum 4B are probably related to this phenomenon. Also, high levels of thermonuclear tritium have

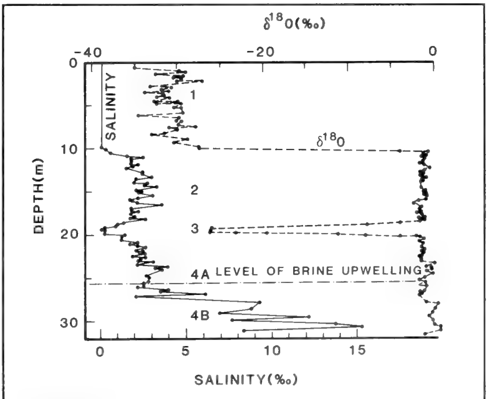

FIGURE 8: Salinity and $\delta^{18}O$ profiles in ice core 83-1, West Ward Hunt Ice Shelf (Jeffries et al. 1988A) (Reproduced by courtesy of the International Glaciological Society from Annals of Glaciology 10, p. 70, Figure 2).

levels of thermonuclear tritium have been found in Stratum 4B suggesting: (1) recent (post-1963) bottom accretion of sea ice; and (2) that brine in Stratum 4B is from deeper in the ice shelf at this location (Jeffries *et al.* 1988A). It was noted earlier that ice temperatures indicate a total ice thickness of almost 45 m at the site of ice core 83-1; the top of Stratum 4 is at a depth of 20.18 m, hence the sea ice might be as much as 25 m thick.

Strata 2 and 4 are separated by a narrow layer of low salinity, low $\delta^{18}O$ ice (Figure 8). This layer, Stratum 3, is composed of fresh and brackish ice (Table 5; Figure 7). This layer has been termed 'non-saline basement ice' (Jeffries *et al.* 1988A). The similarity between the $\delta^{18}O$ values and salinity of Strata 2 and 4, and the thinness of Stratum 3, suggest that the accretion of the latter was a relatively brief interruption of the growth of the sea ice. In the absence of Stratum 3, the sea-ice layer would be as much as 35 m thick.

East Ward Hunt Ice Shelf

The data for East Ward Hunt Ice Shelf are from four ice cores, all drilled in Hobson's Ice Island (Figure 3A) - one of a number of ice islands that calved from East Ward Hunt Ice Shelf in 1982-1983 (Jeffries and Serson 1983). Of the four ice cores, only 86-2 was drilled in a depression.

The specific electrical conductivity (SEC) and ^{18}O data are summarized in Table 6. In contrast to most of the ice in West Ward Hunt Ice Shelf, the ice cores have $\delta^{18}O$ values that are close to those of local precipitation, with SEC/salinity values that are 2-3 orders of magnitude lower than those in the West Ice Shelf. On the basis of the $\delta^{18}O$ values, the ice cores are almost wholly composed of fresh ice, with the exception of 86-1 and 86-2, which contain a small amount of brackish ice (Figure 9). SEC and $\delta^{18}O$ profiles in ice core 87-1 are shown in Figure 10. Tritium activity in ice core 87-1 has yet to be measured; however,

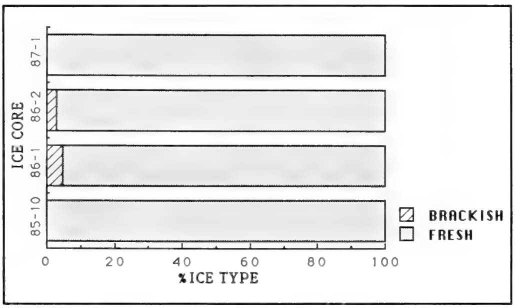

FIGURE 9: Percentages of fresh and brackish ice in ice cores from East Ward Hunt Ice Shelf.

in ice core 85-10 (drilled through the entire thickness of Hobson's Ice Island), high levels of tritium were found in the lowermost 5 m of ice.

TABLE 6: SUMMARY OF SPECIFIC ELECTROLYTIC CONDUCTIVITY (SEC) AND ^{18}O CONTENT OF ICE CORES IN EAST WARD HUNT ICE SHELF/HOBSON'S ICE ISLAND.

ICE CORE	SEC RANGE ($\mu S\ cm^{-1}$)	MEAN SEC ($\mu S\ cm^{-1}$)	$\delta^{18}O$ RANGE (^{o}/oo)	MEAN $\delta^{18}O$ (^{o}/oo)
85-10 (42.06 m)	2.18 to 32.80[1]	7.16 ± 4.35	-34.1 to -25.6	-29.8 ± 1.8
86-1 (38.67 m)	1.52 to 252.0	11.55 ± 32.76	-33.8 to -24.1	-29.5 ± 1.8
82-2 (33.97 m)	1.05 to 274.0	6.33 ± 25.42	-34.6 to -24.5	-29.8 ± 1.9
87-1 (38.80 m)	1.12 to 10.12	3.30 ± 1.51	-32.6 to -26.1	-29.6 ± 1.6

[1] A salinity of 0.1^o/oo is equivalent to a SEC value of ~165.0 μScm^{-1}.

FRESH, BRACKISH AND SEA-ICE GROWTH BENEATH MLSI AND WARD HUNT ICE SHELF

The analysis of ice cores drilled in Ward Hunt Ice Shelf indicates a considerable contrast between ice-types found in the west shelf and the east shelf. The predominance of sea ice and fresh ice in the west and east shelf, respectively, is, in turn, a sharp contrast to the MLSI which is predominantly brackish ice. In this section, the processes responsible for these contrasts will be discussed

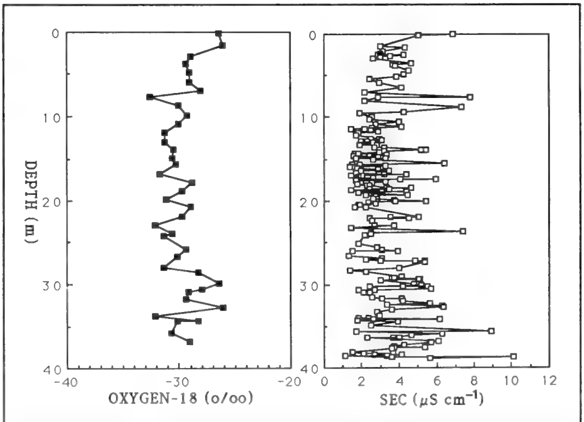

FIGURE 10: Oxygen-18 and specific electrolytic conductivity (SEC) profiles in ice core 87-1, Hobson's Ice Island/East Ward Hunt Ice Shelf.

briefly, with particular emphasis on ice growth arising from water stratification associated with under-ice melt-pools and floating ice dams.

Under-Ice Melt Pools and MLSI Growth

If, as we believe, there are inverted depressions on the bottom of MLSI, then there is a potential for the formation of under-ice melt-pools. This situation, where a layer of low-salinity water floats upon a seawater layer and under the ice has been observed quite often below pack-ice floes (Untersteiner and Badgley 1958; Hanson 1965). It has not been directly observed below MLSI, but it is believed to be quite common (Jeffries and Krouse 1988). This is supported further by data from this study.

In an under-ice melt-pool, with each water layer very near freezing, heat transfer generates ice, either directly or from buoyant supercooled water (Martin and Kauffman 1974). The ice growth occurs in the low-salinity water layer, which must also have negative $\delta^{18}O$ values; hence, the ice has negative $\delta^{18}O$ values and low salinity. If the low-salinity, ^{18}O-depleted water is confined to the inverted depressions then, as we have observed, the depression ice will be less saline and have more negative $\delta^{18}O$ values than hummock ice.

Brackish ice is apparently more common in depressions than hummocks, but it is found in hummocks. This suggests that water stratification is not confined to inverted depressions, but can exist beneath the entire ice sheet. Since the water salinity and ^{18}O content is seasonally variable, associated with ice and snow-melt runoff in summer, water stratification under the entire ice sheet will most likely occur in summer. The seasonality of water properties gives rise to seasonal or annual layers in the MLSI (Jeffries and Krouse 1988).

The seasonality of water properties is not always a brackish water-seawater alternation. Apparently, MLSI can be underlain year-round by brackish water, giving rise to 100% brackish ice, e.g. ice cores 84-3 and 85-5. Further evidence of the year-round persistence of brackish water was obtained at the site of ice core 85-5, where a sample of water that entered the borehole on completion of drilling had a $\delta^{18}O$ value of -24.6°/oo, i.e. brackish water. This occurred in early May, before the onset of melting and runoff.

On the other hand, at some locations the MLSI is clearly underlain by seawater most of the time, e.g. the Nansen Ice Plug (Figure 2B; ice cores 84-4 and 86-4). Water that entered the 86-4 borehole had a $\delta^{18}O$ value of -2.7°/oo. In contrast, water that entered the borehole in deformed MLSI at the site of ice core 85-3 (Figure 2A) had a $\delta^{18}O$ value

of -12.0°/oo. This brackish-water value corresponds with the large amount of brackish ice found in the depression ice, and also with the brackish ice found at the bottom of the hummock ice (Figure 6). Thus, once deformation has occurred and the ice has consolidated, deformed MLSI also forms a stable environment for under-ice melt-pools.

The MLSI data indicate that there can be considerable variation in water properties at a given site, and also great variation between locations. The latter point also applies to Ward Hunt Ice Shelf, where under-ice water stratification is most likely related to the outflow of freshwater from behind a floating ice-dam.

Ice-Dams and Water Stratification

At the mouth of Disraeli Fiord, Ward Hunt Ice Shelf acts as a floating dam preventing the free exchange of fiord surface water with the Arctic Ocean. In consequence, a unique form of water stratification exists, with a 44 m deep freshwater layer (equivalent to the ice-shelf draft) overlying the deeper seawater (Keys 1978; Jeffries 1985). This phenomenon is illustrated conceptually in Figure 11.

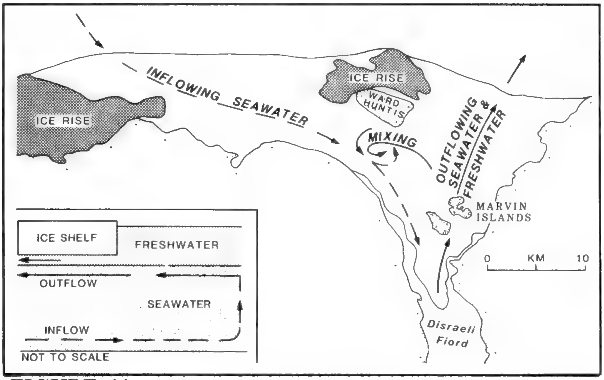

FIGURE 11: Water circulation beneath Ward Hunt Ice Shelf inferred from ice core analysis (Jeffries et al. 1988A). The insert represents the ice-shelf dam and associated water stratification in Disraeli Fiord. (Reproduced by courtesy of the International Glaciological Society from Annals of Glaciology, Vol. 10, p. 72, Figure 6.)

In Disraeli Fiord itself, platelet ice has been found to grow in supercooled water immediately above the halocline and then float upward to the surface of the fiord (Keys 1978). This was first observed in 1967, and the process was suggested as the means by which brackish ice grew at the bottom of the ice shelf (Lyons *et al.* 1971). For this to occur, freshwater or brackish water would have to flow out of Disraeli Fiord beneath the ice shelf. This is most likely to occur in the summer when meltwater runoff into the fiord is at a maximum.

The contrasting ice-core data for West and East Ward Hunt Ice Shelf is considered to be a proxy record of variations in water circulation and bottom freezing beneath the

ice shelf (Jeffries *et al.* 1988A). The great thickness of sea ice in the West Ice Shelf is a record of sea-ice accretion associated with the flow of seawater below the ice shelf into Disraeli Fiord. Seawater flowing out of the fiord is directed below the East Ice Shelf; however, the East Ice Shelf is not underlain directly by a layer of seawater or brackish water, but by a layer of freshwater from the surface of Disraeli Fiord. The high level of tritium at the bottom of the ice indicates the recent flow of freshwater, with associated ice accretion.

Possibly, in the East Ice Shelf, ice growth resulting from the presence of this freshwater layer has been accompanied by surface ablation over a period of 450-500 years. As a result, freshwater ice has completely replaced any sea ice that originally grew to the east of Ward Hunt Island. This process of vertical ice migration is corroborated by the discovery of sponges and plant material, with radiocarbon dates of 400-450 years, at the ice surface adjacent to Ward Hunt Island (Crary 1960).

While the West and East Ice Shelf are underlain almost exclusively by seawater and freshwater respectively, there would appear to be variable mixing of inflowing seawater and outflowing freshwater ice in the region south of Ward Hunt Island. This would account for the variability of ice-types in this region, i.e., ice core 86-8 and "brackish basement ice" (Lyons *et al.* 1971).

The great thickness of sea ice in the West Ice Shelf and of freshwater in the East Ice Shelf suggest that the pattern of water circulation and ice accretion beneath the ice shelf has been quite consistent over a long period of time. However, Stratum 3 (Figure 10) in the West Ice Shelf suggests that water stratification and associated freshwater and brackish ice growth once occurred in this region. Jeffries and Krouse (1984) suggested that this occurred during an exceptionally warm climatic period when the volume of freshwater flowing into and out of Disraeli Fiord was far greater than today.

At Disraeli Fiord, Ward Hunt Ice Shelf lies across the entire mouth of the fiord and gives rise to a pronounced water stratification. At Ayles Fiord, Ayles Ice Shelf occupies about 75% of the fiord-mouth, with MLSI occupying the rest (Figure 2B). Conceivably, water-stratification also exists in Ayles Fiord but, rather than leaking out uniformly below the ice shelf, the low-salinity water tends to flow out beneath the MLSI. As in Disraeli Fiord, the flow of low-salinity water is likely seasonal, with a wedge of freshwater or brackish water penetrating far beneath the ice in summer, and retreating again in winter. In view of the

apparently large amount of brackish ice in Ayles MLSI, there is probably greater mixing of freshwater and seawater so that the ice is underlain mostly by brackish water. In addition to the layer of low-salinity water flowing out uniformly below the MLSI in summer, probably pockets of it will persist in inverted depressions on the ice bottom. Thus, ice growth of Ayles Fiord MLSI might arise from a combination of influences, i.e., water-stratification associated with both under-ice melt-pools and floating ice-dams.

DISCUSSION AND CONCLUSION

We noted earlier that undeformed multi-year pack ice floes commonly have a steady-state thickness of 2.5-5.0 m (Maykut and Untersteiner 1971). Data presented here suggest that extensive areas of MLSI exceed this thickness, while the thickness of sea ice in West Ward Hunt Ice Shelf far exceeds any thick sea ice found to date. Thick sea-ice floes (>5 m) have been found occasionally in the Arctic Ocean (Walker and Wadhams 1979), and there appears to be little doubt that they were correct in suggesting that they originate at very high latitudes, e.g., the north coast of Ellesmere Island.

To account for thick sea-ice growth on thermodynamic grounds alone, Walker and Wadhams (1979) modified the Maykut and Untersteiner sea-ice growth model. With oceanic heat flux set to zero and annual snowfall at 1.0 m, an ice thickness of 12 m was reached in 65 years, and a thickness of 20 m after 200-300 years. This type of model might apply to the Nansen Ice Plug and West Ward Hunt Ice Shelf and account for the thick sea-ice growth there.

Thick sea-ice growth as described in the previous paragraph would be very slow. Possibly large areas of MLSI have grown quicker, in a manner independent of Maykut-Untersteiner-type ice-growth models (Jeffries and Krouse 1988). Data presented here suggest that water stratification is common below MLSI; hence MLSI growth can be accounted for by a double-diffusion process similar to that described by Martin and Kauffman (1974). In this case, the annual transfer of meltwater from the ice surface and surrounding land to a cold-sink below the ice will lead to thick sea-ice growth in a relatively short period of time. Jeffries and Krouse (1988) indicate a mean thickening-rate of 400 mm a^{-1}.

The growth of MLSI attached to thicker ice shelves raises the possibility that some MLSI growth might be associated with the operation of an "ice pump" (Lewis and Perkin 1983, 1986). Briefly, if sea water that has been in contact with an ice shelf at depth is raised, then as pressure reduces, it might become supercooled in relation to the in situ freezing point and could provide a heat-sink for ice growth within the water column. This has been observed in Antarctica, and it might occur off the north coast of Ellesmere Island.

The ice-pump principle is also relevant to the bottom topography of the ice. Lewis and Perkin (1983) describe the ice-pump as melting ice from a pressure ridge keel and depositing ice within a lead, with an overall tendency to produce a uniform ice thickness. They note that it is not necessary to have open water to start an ice pump of this type; any variation in ice thickness causing freezing-rate variations at the ice/water interface is sufficient. If applied to MLSI this would suggest a tendency toward a flat bottom-side on the ice. The ice-property data presented here suggests that this is not the case. Furthermore, Jeffries *et al.* (1988B) have observed that the entire thickness of hummock ice is colder than depression ice, and suggest that heat conduction through hummocks will be greater than through depressions. Thus, despite considerable ice growth by double-diffusion processes below depressions, greater ice growth will occur on hummock keels, and an undulating bottom topography will be maintained.

The foregoing discussion is necessarily speculative because studies of the heat and mass balance of MLSI, or of any other kind of thick sea ice are lacking. Field-data collection and subsequent modelling of the heat and mass balance of this thick ice would provide considerable insight into ice-growth processes below the ice - processes responsible for the thick sea-ice growth, and surface processes that are responsible for the initiation and perpetuation of the surface topography, and perhaps the bottom topography.

Studies of the physical properties of the ice, emphasizing stable-isotope tracing, indicate that such tracing can be usefully applied in sea-ice studies. In this case, it contributed to the disclosure that MLSI is often composed of brackish ice - an important discovery in its own right. It is also significant because there have been few studies of brackish ice anywhere. Hence, MLSI offers the opportunity to study not only the thermodynamics of thick brackish and sea ice, but also the physical and structural properties of this type of ice. With regard to the latter, Jeffries and Krouse (1988) suggested that structural characteristics in MLSI may govern the preservation of annual salinity layers. Indeed, 'brackish basement

ice' in Ward Hunt Ice Shelf apparently has none of the platy substructure characteristic of sea ice (Lyons *et al.* 1971). Thus, brine-drainage is probably limited. MLSI represents an opportunity to examine these sorts of physical-structural characteristics.

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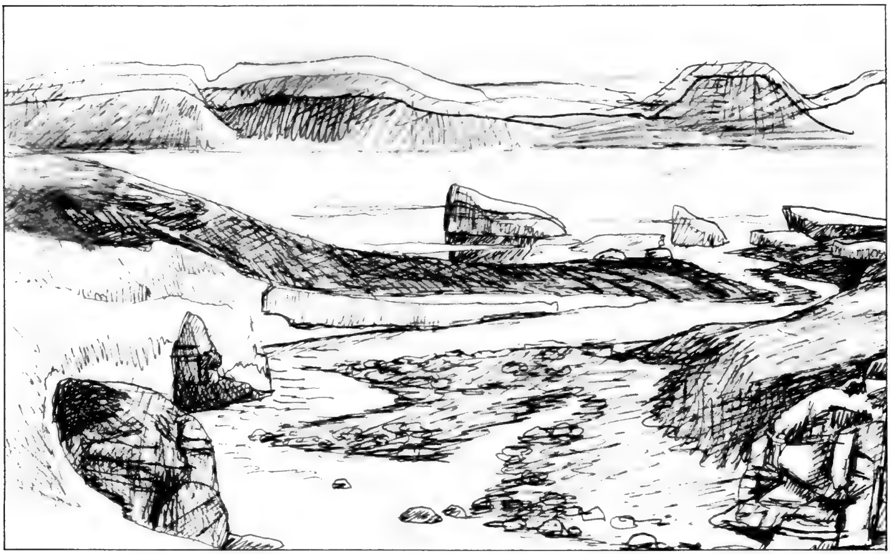

Illustrated by Brenda Carter

ACOUSTIC RESEARCH IN THE CANADIAN ARCTIC: SOUNDING THROUGH SEA ICE AND ICEBERG DETECTION

Phillipe de Heering[1]

Abstract: The paper presents photographic documents illustrating two acoustic research projects recently completed in the Canadian Arctic Islands: non-contact through-the-ice sounding and iceberg sonar-detection. A brief description of the goals and results of these projects is provided.

Résumé: On présente des documents photographiques relatifs à deux projets de recherches récents ayant trait à l'Arctique canadien: le télésoundage des mers arctiques et la détection sonar d'icebergs. On fournit également une brève description des buts et résultats desdits projets.

INTRODUCTION

During the last few years, several acoustic research projects have been carried out in the Canadian Arctic for both commercial and military applications. While the military work results directly from an increased perception of the strategic importance of this part of the world, the commercial aspects of the research are more diversified, and include geophysics, hydrography and the sonar-detection of ice-hazards from ships navigating the region.

I provide briefly here a photographic description of selected aspects of two such projects that I and my colleagues have completed. The scientific results of this work have been discussed elsewhere (De Heering 1987; De Heering and Sutcliffe 1987) and will be merely outlined below.

SOUNDING THROUGH SEA ICE

The first program, "Non-Contact Through-The-Ice-Sounding", carried out for the Canadian Hydrographic Service (Fisheries and Oceans Canada), dealt with the development of an acoustic approach to airborne sounding of arctic waters. This effort was motivated by the fact that the sounding of Canadian Arctic waters presents the special problem that these

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waters - which are covered in many areas by ice throughout much of the year - are not readily accessible to hydrographic ships. For this reason, Fisheries and Oceans Canada is actively pursuing research and development related to sounding under these special conditions.

For example, current over-ice hydrographic surveys are carried out from a helicopter (Bell 206-B) that bears a special echo-sounding device. To take one sounding, the helicopter first lands, then an electro-acoustic transducer carried by a mechanical ram outside the helicopter is applied against the (often snow-covered) ice. The system then measures the delay between the transmission of an acoustic impulse and the reception of an echo, which is a measure of the water-depth. This, and similar systems feature relatively slow mapping-rates, as the vehicle needs to stop at each sounding point.

To circumvent this problem, an alternative approach aiming at non-contact sounding from a helicopter in flight was developed and tested. This technique, (Figure 1) involves the transmission of an acoustic sounding impulse in the water resulting from the impact on the ice of a high-speed bullet shot from the helicopter. The pulse reflected by the seafloor is received by a specially designed microphone system flown above the ice. The water-depth can be deduced from the echo-delay and other relevant parameters.

The field work was carried out from two locations in the Canadian Arctic Islands: the first phase during April 1984 near Browne Island; and the second on Intrepid Bay, Cornwallis Island. Figure 2 shows our camp on the sea ice established in April for preliminary tests of the sounding concepts. The photograph is taken from a 7.6 m high platform for shooting at the ice in the bullet-impact acoustic measurements. The bullet-impact sounds were received by hydrophones suspended through the ice in the water, then recorded and analyzed (Figure 3). Figure 4 illustrates the method used to acoustically-decouple from the ice a microphone used for airborne reception of the seafloor echoes. The prototype transmission and receiving devices were mounted on a helicopter (Figures 5, 6). The former consists of a .30 calibre Weatherby gun mounted on the right side of the helicopter, whereas the latter is a "bird" suspended from the helicopter and instrumented with two microphones and an altimeter. The received echoes were recorded on board the helicopter and analyzed on the site and in Ottawa.

Very encouraging results have been obtained, but more work is needed to demonstrate the feasibility of the approach.

ICEBERG DETECTION

The second program dealt with shipborne sonar detection (Figure 7) of icebergs in ice-free and ice-covered arctic waters. The field trials were carried out in the Lancaster Sound-Baffin Bay area from the icebreaker M.V. *Arctic* (owned by Canarctic Shipping Company Limited). The usefulness of sonar iceberg-detection results from the fact that the propagation path of underwater sound is distinct from that of the propagation path for electromagnetic radar signals, so that fades of the two systems are expected to be statistically independent. Thus, sonar and radar combined detection statistics would be significantly more favourable than those of each of the sensors alone, in their range of overlap. Note too that some 90% of the iceberg-mass is underwater, thereby providing a larger target-area for waterborne signals than for airborne signals. Also, in the short range, radar may suffer reduced performance due to unfavourable geometry, while the sonar ordinarily does not.

Furthermore, visual detection of icebergs (Figure 8) is often made difficult by the polar night or by fog (Figure 9), whereas the ice-cover often contributes radar clutter which is difficult to distinguish from echoes of small bergs. In the course of summer field work in 1984 and 1986, during the passage between Nanisivik on northern Baffin Island and Antwerp, Belgium, iceberg acoustic-echo data were obtained by means of a modified fish-finding sonar made by C-Tech, Cornwall (Figure 10) and operated together with a specially-configured data-acquisition system (Figure 11).

Data-acquisition and analysis trials demonstrate the acoustic feasibility of sonar detection of icebergs from a ship at ranges of 50-2,000+ m. In addition, the in situ acoustic cross-section (or target-strength) measurements, together with the acoustic environment measurements, which were undertaken during the tests, provide a realistic basis for the design of an active sonar dedicated to iceberg detection.

ACKNOWLEDGEMENTS

Logistical support for trials during the first program was made possible by the Polar Continental Shelf Project (Energy, Mines and Resources Canada) in Resolute. Without their

support, the field work discussed here would not have been carried out. Canarctic Shipping Company Limited of Ottawa and Transport Canada supported the second program.

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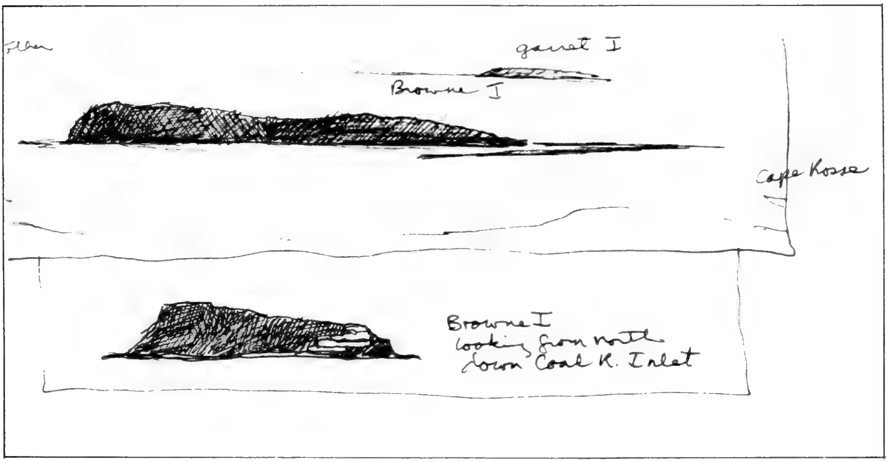

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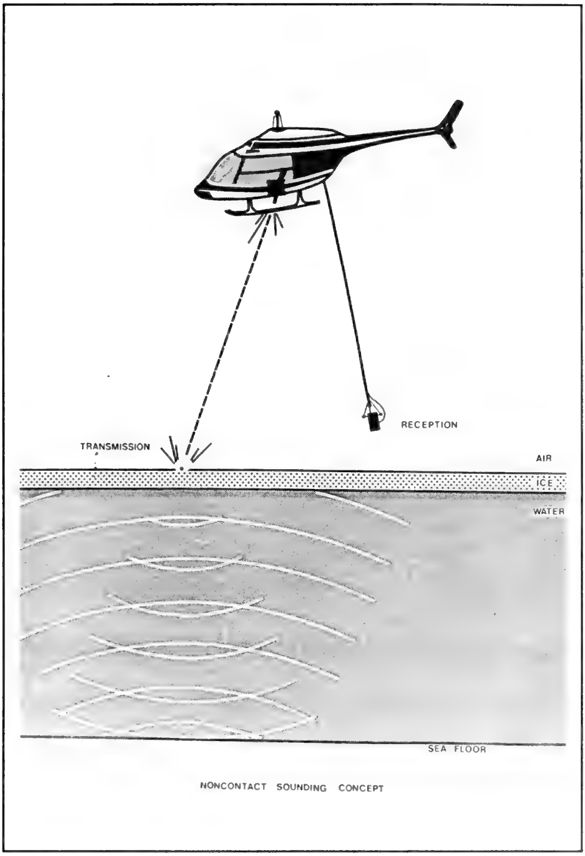

FIGURE 1: Non-contact sounding concept using a helicopter.

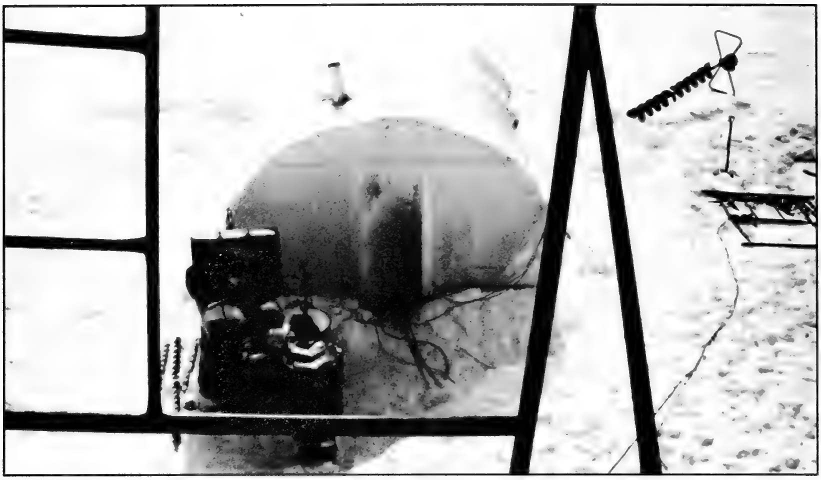

FIGURE 2: Camp on sea ice, April 1984, in the vicinity of Browne Island, southwest of Resolute Bay.

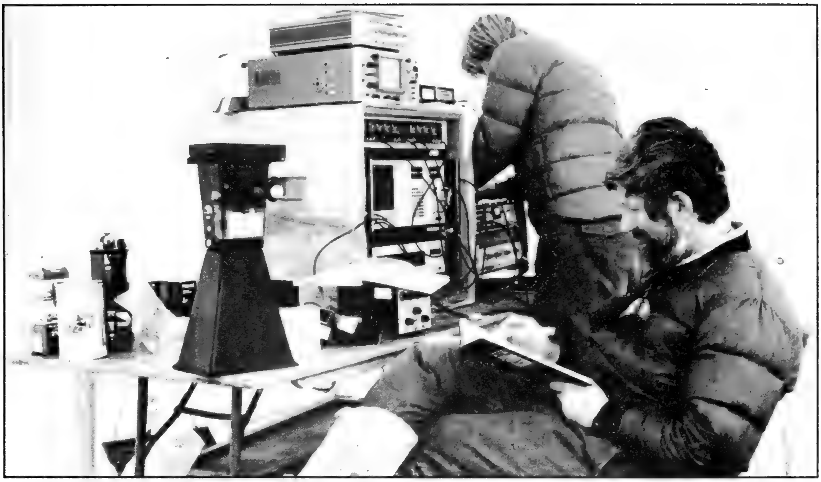

FIGURE 3: Facilities (shelter and stove) in the Camp made available by the Polar Continental Shelf Project resulted in a comfortable environment.

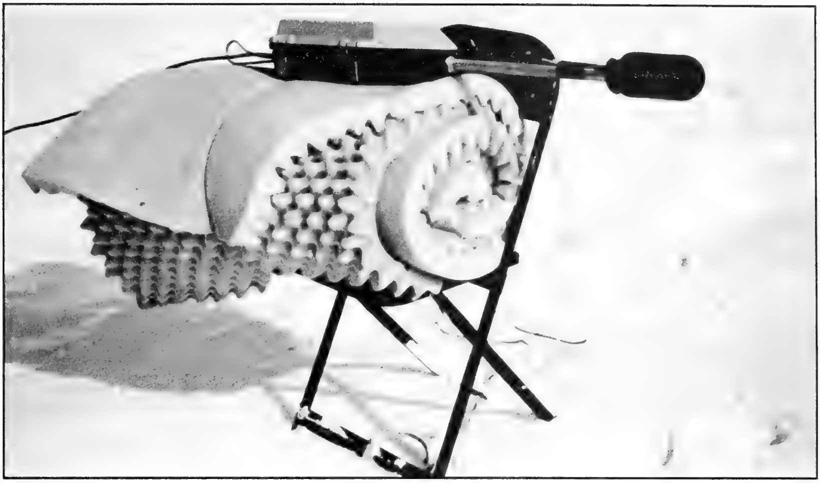

FIGURE 4: Receiving microphone above the sea ice.

FIGURE 5: Prototype - transmitting system. Rifle attached to helicopter.

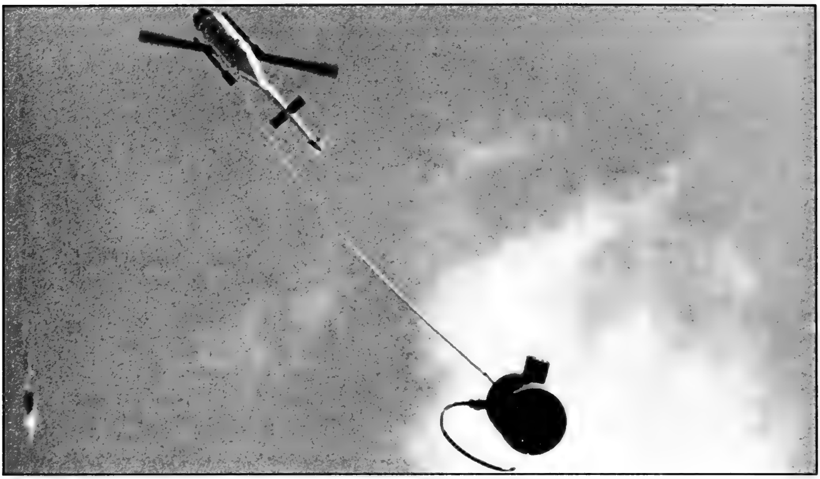

FIGURE 6: Prototype - receiving system suspended from helicopter.

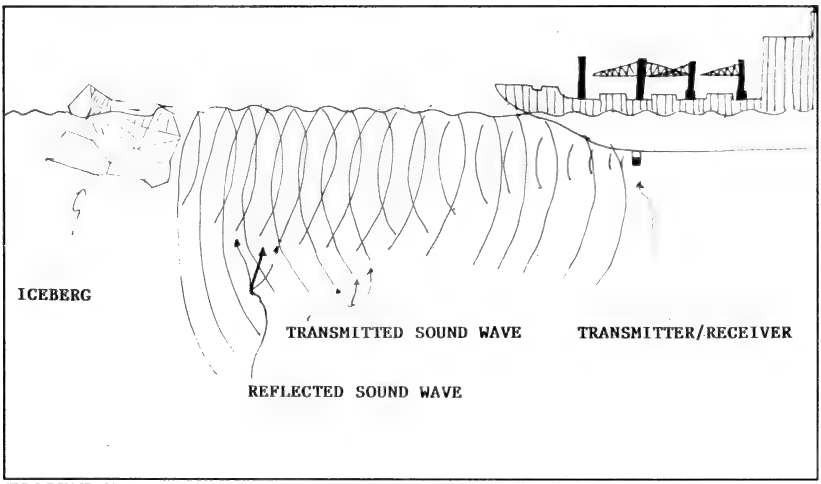

FIGURE 7: Principle of iceberg detection using sonar.

FIGURE 8: Grounded iceberg off bow of M.V. Arctic.

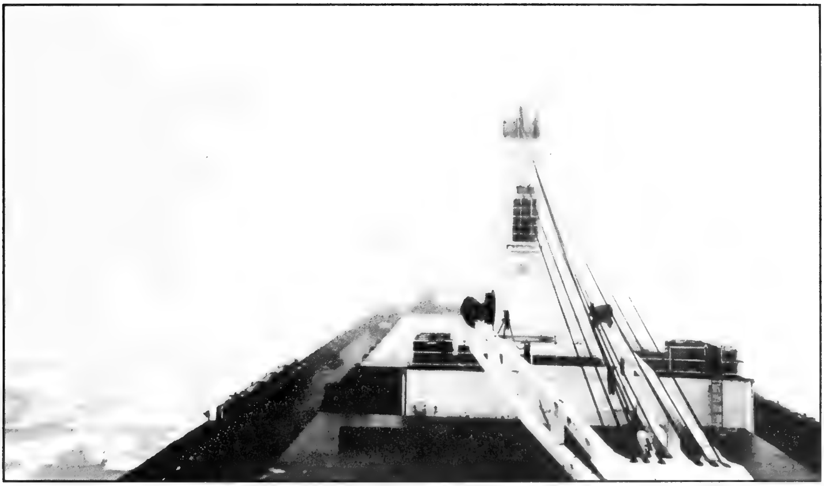

FIGURE 9: Testing during foggy conditions.

FIGURE 10: Sonar modified for detecting icebergs.

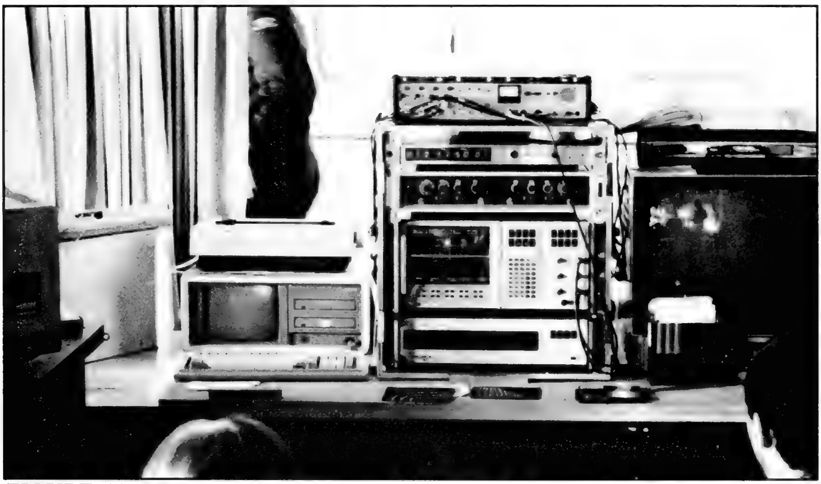

FIGURE 11: Data-acquisition systems aboard M.V. Arctic operated in combination with the sonar.

ARCTIC ICE CORES: PUTTING PRESENT CLIMATE INTO PERSPECTIVE

Roy M. Koerner[1]

Abstract: Our present climate is far from normal when viewed in terms of the past 100,000 years of record. Data are based on oxygen-isotope ratios or "delta-values" for ice-core samples from various levels in a core from the Agassiz Ice Cap on northeastern Ellesmere Island. The Agassiz data indicate that: (1) climate there has been colder then present for about 80,000 of the past 100,000 years; (2) ice caps in the Arctic Islands melted completely during the last interglacial; and (3) the climate of the last 60 years has been colder than average for the last 10,000 years, but warmer than average for the last 1,000 years.

Although global circulation models predict that greenhouse gases (e.g. carbon dioxide) will cause a warming of several degrees Celsius in the High Arctic during the next century, presumably this warming would not persist long enough to completely melt Canadian Arctic Islands ice caps. Perhaps the early phase of the last interglacial may be the best analogue for such warmer conditions.

Résumé: Le climat actuel est loin d'être normal si on le considère à la lumière des 100,000 dernières années. Les données sont basées sur les rapports d'isotopes de l'oxygène ou "valeurs delta" pour des échantillons pris à différents niveaux sur une carotte de glace provenant de la calotte glaciaire d'Agassiz, sur le nord-est de l'île Ellesmere. Les données d'Agassiz montrent que: (1) le climat y a été plus froid qu'actuellement pendant environ 80,000 des 100,000 dernières années, (2) les calottes glaciaires dans les îles de l'Arctique ont fondu complètement au cours du dernier interglaciaire, (3) le climat des 60 dernières années a été plus froid que la moyenne des 10,000 dernières années, mais plus chaud de la moyenne des 1000 dernières années.

Bien que les modèles de circulation globale prévoient que les gaz à effet de serre (par ex., le gaz carbonique) entraîneront un réchauffement de plusieurs degrés Celsius dans le Haut-Arctique au cours du prochain siècle, ce réchauffement ne persistera probablement pas assez longtemps pour faire fondre totalement les calottes glaciaires des îles de l'Arctique canadien. La première phase du dernier interglaciaire constitue peut-être la meilleure analogie de ces conditions plus chaudes.

INTRODUCTION

Glaciers and ice sheets throughout the world are strongly related to climate. In the past, during periods of intense cold, ice masses have expanded to cover large parts of North America and Europe. Mountain glaciers have also expanded during these times, and it appears from the ocean record that over the past million years the more normal condition is for much colder conditions than today, with ice sheets covering large parts of Canada. However, these are the most dramatic changes, and it must be realized that climate changes through a wide range of wavelengths and amplitudes, from millennial to decadal and from fractions of a degree to several degrees. Ice sheets contain records of all these changes.

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ICE CAPS AND GLACIERS

An ice or snowfield becomes "permanent" once it is able to survive each summer. To do this, the snowfalls of winter must exceed the ice-melt of summer. Snow survives at high elevations but melts, along with some of the underlying ice, in the lowermost regions. In the more dynamic ice caps - those with outlet glaciers reaching the sea - some ice may break off and melt in the ocean.

Ice formed in the accumulation area moves down toward the underlying rock as it is buried under subsequent snowfalls. It also moves out toward the margin. The ice in the ablation zone also moves toward the margin, but its vertical component is upward, replacing the ice that melts. The thickness of the annual snow-layer at the surface varies from about 1.5 m close to Baffin Bay to as little as 0.15 m on parts of the more northerly ice caps on Ellesmere and Axel Heiberg islands. In the ablation zone, between 1 m and 3 m of ice melts at sea level each summer. The equilibrium line (where snow accumulation equals snow melt) varies in elevation from 900 m to 1300 m above sea level in the Canadian Arctic Islands.

ICE CORES

Because the vertical component is almost entirely downward at the top of an ice cap, cores for climate studies are best taken there, as they suffer minimal disturbance by flow over irregular bedrock. Such cores contain records of snowfall beginning with the time the ice cap began its growth and extending to the present day. Everything that falls with the snow, including dust, pollen, and soluble salts is gradually buried. Several surface-to-bedrock cores, spanning a time interval of about 100,000 years over a depth increment of 100 m to 300 m, have been drilled in the Arctic Islands.

As it is buried by subsequent snowfalls the surface annual-layer thins by compression under increasing thicknesses of overlying snow until it becomes ice at a depth of about 60 m. At greater depths the layer continues to thin due to ice movement. In an ice cap 150 m thick, an annual-layer at 135 m is about 10,000 years old and less than 1 mm thick. Thus a core cannot be dated by simply dividing the core length by the surface annual-layer

thickness. Instead, time-scales are determined by detecting seasonal swings in the concentration of micro-particles or ions in the ice, and by picking up high levels of acidity in the cores attributable to well-known, dated volcanic eruptions. These two methods date the ice back to about 7,000 years. Beyond that, the time-scale becomes increasingly inaccurate. We can only get an approximate date for any particular level by comparison with the better-dated Camp Century core in Greenland (Dansgaard *et al.* 1982) or with the fairly well-dated ocean cores (Hammer *et al.* 1980).

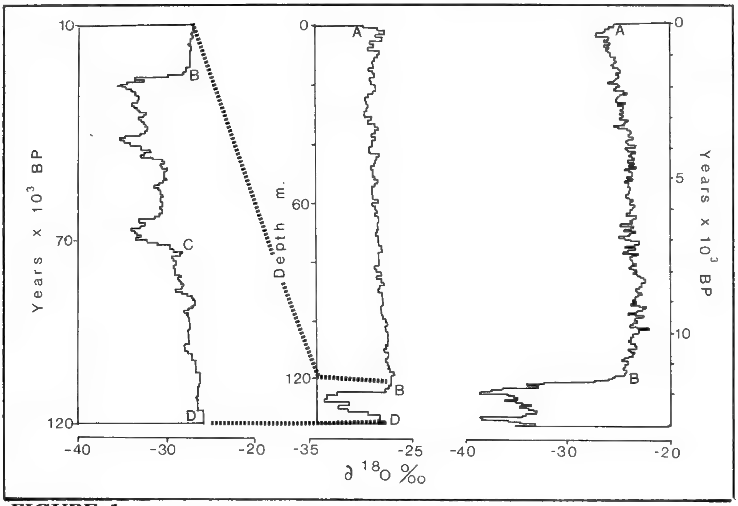

FIGURE 1: Oxygen isotope values for a core from the top of Agassiz Ice Cap (Ellesmere Island) drilled in 1979. The figure is in three sections. The middle section shows delta-values on a linear depth-scale from the snow surface to the bed underneath. The very cold values just below 'B' represent ice deposited during the last (Wisconsin) glacial period when the Laurentide Ice Sheet covered most of Canada.

The section on the left is a magnified version of the lowermost part of the ice and is again plotted on a linear depth-scale. Approximate ages of the ice are shown on the vertical axis. 'B' to 'C' represents the last glacial period and 'C' to 'D' (the bed) represents part of the last (Sangamon) interglacial period.

The section on the right is a linear time-scale plot of the delta-values of ice deposited during the last 12,000 years. The 'A' to 'B' section consists of ice deposited during the present interglacial period (Holocene). Note it shows a general cooling which persisted to within a hundred years of the present. Present conditions (the last 50 yrs) are shown as cooler than the greater part of the past 10,000 years.

Perhaps the most important climatic indicator in the ice cores is the *oxygen isotope ratio* or "delta-value". The more negative the delta-value, the lower the temperature the snow formed at. Figure 1 shows a delta-value profile for a core from the Agassiz Ice Cap on northeastern Ellesmere Island. The core is from the top of the ice cap at an elevation of 1,702 m above sea level.

The profile can be broken into three major sections: (1) an uppermost section (0-122 m) with "warm" delta-values; (2) an intermediate section (122-128 m) with very "cold" delta-values; and (3) a lowermost section (128 m to bed) where the delta-values gradually increase toward the bed. The uppermost section was deposited during the Holocene period (the last 10,000 years). The intermediate section represents the coldest period of the last (Wisconsin) glaciation from 10,000 to 70,000 years ago. The temperatures during this period were several degrees colder than today. The lowermost section was deposited during the last (Sangamon) interglacial period in warmer conditions than today but also during the cooling transition period that brought the Wisconsin glaciation. When the delta-profile is examined in more detail, the values suggest that, once the ice cap began its growth, the air temperature above gradually cooled toward the peak of the last glaciation. It appears that the ice cap started its growth sometime during the last interglacial. Any ice cap from the previous glacial period must have melted completely during the last interglacial. Other evidence in the core (e.g. pollen concentrations and the texture of the ice itself) supports this interpretation. The most recent 10,000-year section of core shows a period of maximum warmth closely following the dramatic emergence from glacial conditions. The climate has been cooling ever since.

A few important points about these profiles from the Arctic Islands are relevant to today's debate about the direction in which climate may be heading: (1) The climate at the drill-site has been colder than today's for about 80,000 of the past 100,000 years. We tend to view our current climate as "normal"; however, it is far from normal when viewed in terms of 100,000 years of record. Using ocean-core records we might even say the planet's climate is due to return to the "normal" condition of an ice age. What we should be seeking is not the cause of ice ages but the cause of interglacial periods. (2) If ice caps in the Canadian Arctic Islands melted completely during the main part of the last interglacial then that period must have been substantially warmer and/or longer than the present one. (3) The climate of the last 60 years has been colder than average for the last 10,000 years but warmer than average for the last 1,000 years.

Our view of present climate depends very much on our terms of reference. Predicting climate is often considered, particularly by the layperson or politician, as the end-product of paleoclimatic research. So a common question is: "What is the climate going to do in the future?" One has to have some kind of answer ready, and it should be based on a long

time-series of high-quality proxy climate data. In our case, delta-value has been used, as it can be reproduced by adding two to four sine waves of different period, amplitude, and phase. Extrapolation can then be made by adding this sine-wave sum or synthesis. The calculations suggest a slight average annual cooling over the next 50 years of about 0.5°C to 1.0°C. Summer cooling in the next 50 years (based on the amount of melting as evidenced by clear ice-layers in the cores) may be slightly more than this. Although the standard error of this forecast is of similar magnitude to the change itself, other calculations based on delta-values from Greenland cores give similar "forecasts" to ours. Anthropogenic effects apart, we should not expect the open sea-ice conditions of the 1940s and the 1950s to occur again. Perhaps we should plan for the most pessimistic side of climate in the Arctic Islands and take the coldest summers from the past 40 years of record as a practical norm.

Computer models suggest that industrial atmospheric pollutants are going to profoundly affect our climate, if not in our lifetime, at least in that of our children. Just over a decade ago it was suggested that industrial pollutants could cause a premature slide into the next ice age; this was the "human volcano" hypothesis. Starting with the premise that volcanic activity causes global cooling, it was argued that dust from industrial activity would have a similar but persistently increasing effect. Our cores contain evidence of volcanic activity, mainly from eruptions in Alaska, Yukon, and Iceland. The eruptions appear as high levels of acidity in the cores. We have been unable, up to now, to demonstrate either a cooling or warming effect of volcanic activity by relating the high acid-levels to changing oxygen-isotope values in the cores. However, Hammer *et al.* (1980) concluded from work on Greenland cores that high acid-background levels in the ice are associated with slightly "colder" delta-values. In other words, climate may change in response to persistent, rather than peak, levels of volcanic activity maintained over many years.

The "human volcano" hypothesis has now been superseded by that of the effect of increasing levels of "greenhouse" gases, particularly carbon dioxide. Global circulation models predict dramatic warming over the next 100 years, particularly in the High Arctic (see McKay, this volume). Ice cores have played their part here also. Greenland cores have shown lower levels of carbon dioxide in ice deposited during the last glacial period. However, this is a chicken-and-egg problem. Do the carbon dioxide changes precede or follow the delta-value changes? Are they a cause or an effect?

CLIMATE MONITORING

Our cores have not yet been analyzed for carbon-dioxide concentrations. However, the Arctic Island ice caps are being used in another way for climatic research: to determine the way climate is heading. Each summer, melting occurs on the ice caps. At sea level, 2 to 3 m of ice may melt and run off onto the surrounding land or into the sea. Melting even occurs at the tops of the ice caps in most years, although it may be for only a few days. Each spring on the Melville South, Meighen, Devon, and Agassiz ice caps, measurements are made of the amount of ice and snow that melted the previous summer and the amount of snow remaining from the previous "year", ending with the last melt of summer. This gives a time-series of ice-melt and snow accumulation for a "balance-year" beginning one August and ending the next. The Meighen and Devon ice cap records now cover 27 years. No significant trends of changing snow accumulation or ice-melt rates can be found in the data, although large year-to-year variations may be burying any slight trend that does exist.

DISCUSSION

The ice-core record (Figure 1) shows a large range of climatic conditions over the past 100,000 years. Compared to the last 10 years, temperatures show a range from about 10°C to 15°C colder 18,000 years ago through 3°C warmer 7,000 to 8,000 years ago, to 5°C warmer more than 100,000 years ago when the ice cap began its growth. On a shorter time-scale, during the period of instrumental record, there is evidence from our cores of a 2.5°C warming between about 1750 and 1950. The warming trend, which has occasionally been identified as carbon-dioxide induced, can be seen as part of a much longer natural one.

Although global circulation models all predict that greenhouse gases will eventually cause a warming of several °C in the High Arctic, the amount of warming varies from model to model. However, the ice-core record suggests that the last interglacial, which may have seen the demise of all Canadian ice caps, may be used to represent an environment in which the level of carbon dioxide is doubled. Various studies of the paleoenvironment from that

period can provide valuable input into estimating the effects of the proposed warming. Data of this nature are already available, much of it within the Quaternary Environments subdivision of the Geological Survey of Canada. However, it must be pointed out that "greenhouse warming" would not persist long enough to completely melt the ice-caps in the Canadian Arctic Islands. The closest scenario of a carbon-dioxide world might, therefore, be the early part of the last interglacial period when the High Arctic ice caps had still not melted completely.

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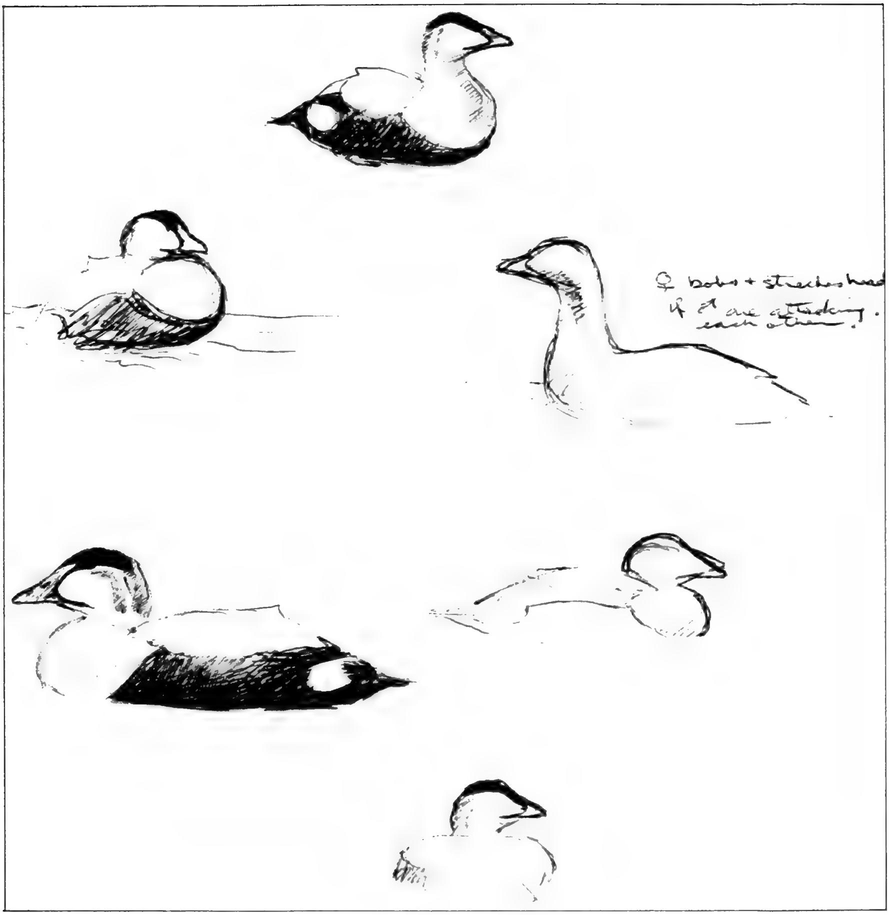

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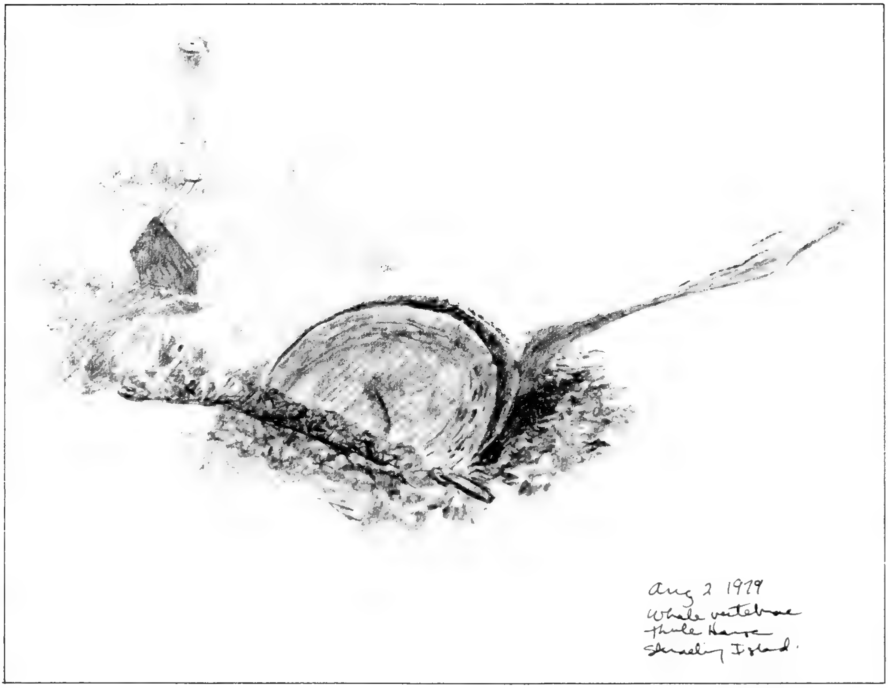
THE ATMOSPHERE



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CLIMATE AND THE CANADIAN ARCTIC ISLANDS

Gordon A. McKay[1]

Abstract: The Arctic climate is harsh by southern Canadian standards but normal for the Inuit. The climate reflects the polar-region energy exchange, and the weather systems that cross the area. Brief summers with long daylight bring welcome periods of warmth and energize the vigorous Arctic microclimates. They also bring thawing soils and hordes of insects. Snowcover and the relative absence of solar radiation contribute to the extreme cold and length of winter. Although cold, wind and drifting snow may curtail activity, winter is often the favoured season for travel since the water and land are both firm. Storms are often most severe near sea coasts where snow and gales may cut access to harbours and settlements and complicate travel in ice-fields. Strong temperature gradients and abundant snow occur in winter across the eastern Arctic. Very light precipitation farther west has led to the expression "polar desert".

Today, much attention is being given to atmospheric change resulting from human activity. "Arctic haze" and climate-warming as a result of the "greenhouse" effect could have enormous impact. Current projections indicate Arctic winters may be up to 10°C warmer by 2050 - much greater than southern-latitude warming. Summer warming would be less, but both the growing and ice-free seasons would be extended, precipitation would increase as would the sea level. Such alterations would greatly affect people, ecosystems and travel within the Arctic.

Résumé: Le climat de l'Arctique paraît rigoureux pour les habitants du sud du Canada, mais normal pour les Inuits. Ce climat est fonction de l'échange d'énergie solaire et thermique de la région polaire et des systèmes météorologiques qui traversent la région. De brefs étés marqués par de longues périodes de lumière du jour apportent une chaleur opportune et stimulent les vigoureux microclimats de l'Arctique. Ils s'accompagnent aussi d'un dégel du sol et d'une multitude d'insectes. La couverture de neige et l'absence relative de rayonnement solaire contribuent au froid extrême et à la longueur de l'hiver. Même si le froid, le vent et la poudrerie risquent de réduire l'activité, l'hiver est souvent la saison préférée pour les voyages, car l'eau et le sol y sont tous les deux à l'état solide. Les tempêtes sont souvent les plus violentes près de la côte, où la neige et les vents forts peuvent couper l'accès aux ports et aux collectivités, ainsi que compliquer les déplacements dans les champs de glace. Dans tout l'est de l'Arctique, il y a en hiver de forts gradients de température et une neige abondante. Plus à l'ouest, des conditions marquées par de très faibles précipitations ont donné naissance à l'expression "désert polaire".

Aujourd'hui on s'intéresse beaucoup au changement atmosphérique attribuable à l'activité humaine. La "brume arctique" et le réchauffement du climat découlant de l'effet de "serre" pourraient avoir d'énormes répercussions. D'après des projections actuelles, en l'an 2050, les hivers arctiques seront peut-être jusqu'à 10°C plus chauds qu'aujourd'hui, réchauffement nettement supérieur à celui du sud. Le réchauffement d'été serait moins élevé, mais tant la saison de croissance que la saison exempte de glace s'allongeraient, la hauteur des précipitations s'accroîtraient et le niveau de la mer monterait. De tels changements auraient d'énormes répercussions sur les gens, les écosystèmes et les déplacements de l'Arctique.

INTRODUCTION

Climate is a major determinant of the character of a region, and it is part of a global system. For example, the Sahara, the Great Plains and Amazonia all reflect strongly their regional climates. The imprint of climate on the Arctic Islands is unmistakable. Arctic climate has challenged mankind throughout history. Cold, ice, permafrost and the effects of an extreme environment on the human body and psyche have been major challenges. Animal and plant life have adapted to the rigors of climate, but occasionally are victims of extremes such as excessive windchill, the occurrence of glaze-ice and an excess or deficiency

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of snowcover. Technologies and materials that are imported into the Arctic were often developed for use in quite different climates. That mismatch has led to many difficulties.

Scientific definition of the Arctic climate began with early expeditions. Posts of the Hudson's Bay Company and the Royal Canadian Mounted Police, provided climate information on a network basis. A formal meteorological network with upper-air soundings was instituted with the establishment of joint Canadian and American weather stations during the Second World War. The existing Canadian network, not only serves the requirements for weather forecasting, but at some locations the atmosphere's chemical composition is measured also, so that changes effected by man might be better understood. The historic and official networks enable the description of the broad features of climate in the Arctic Islands. The complex areal details of those features are now being revealed as supplementary records taken by teams of scientists, oil companies and others fill in the picture.

THE SYNTHESIS OF CLIMATE

The Arctic's climate is relatively unique. It reflects the astronomical control of the sun manifest in terms of incoming and reflected radiant energy and in weather systems. The snow and encompassing water and ice-cover also profoundly influence the climate. Most solar energy incident on snowcover is reflected back to space (Table 1). An appreciable fraction of the remainder is used in the melting and evaporation of snow and ice. The

TABLE 1: REFLECTION COEFFICIENTS FOR TYPICAL SURFACES (after Kondrat'ev 1954, Fritz 1951).

SURFACE	REFLECTIVITY in %
Exposed, continuous snowcover	80
Exposed, melting snowcover	55
Wet, after snow-melt	15
Tundra in the warm season	25
Coniferous forest	12
Complete stratocumulus cloud-cover	56 to 81

energy used in melting or stored in the oceans in summer is not lost, but is released to the atmosphere later as winter sets in. The potential energy input from the sun in mid-summer is similar to that at temperate latitudes, but the daylight period is much longer and the sun at a much lower angle than found farther to the south (Figure 1). The snow surface radiates energy back to space as a black body, resulting in steady net losses over the protracted winter and contributing to the formation of highly-stable cold air-masses. The net result is a long, cold winter and a short, cool summer.

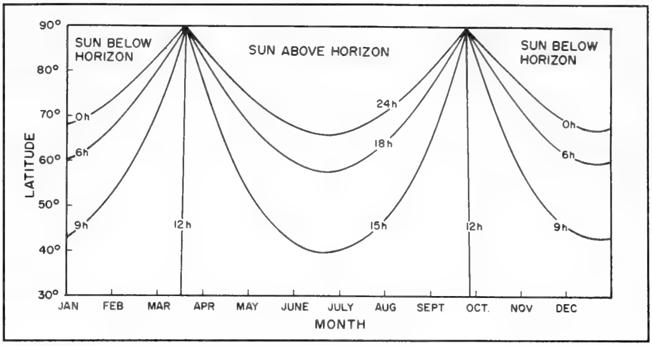

FIGURE 1: Duration of daylight (hours).

Not only the frozen seas, but also the Atlantic and Pacific Ocean leave their mark on the climate. The eastern Arctic is mildest and receives most precipitation because of the nearby open water of the North Atlantic Ocean. The western regions are much drier, and the northwest is strongly influenced by the adjacent multiyear ice cover of the ice-covered Arctic Ocean (see Jeffries *et al.*, this volume).

Land relief and surface-cover also helps to shape climate. Mountains act as barriers to air flow, stimulating precipitation on their windward side, and contributing to warmer, drier climates downwind (see Alt and Maxwell, this volume). They produce katabatic and foëhn winds. Along with wind, mountains serve to augment or to decrease precipitation. On one occasion International Biological Program scientists on Devon Island observed a marked foëhn wind accompanied by rapid snow-melt causing lemmings that had not moved to higher ground to drown. Cloudiness, precipitation and wind speeds generally increase with elevation, whereas air temperature and moisture content decrease. Under cooling conditions, colder air tends to flow into and accumulate in valleys, causing strong inversions that favour the accumulation of pollutants and the formation of ice-fog. The acceleration, damming and deflection of air due to topographic features can produce unusual local climates or microcli-

mates. The surrounding sea ice reaches its greatest extent in April, at which time its surface features may be indistinguishable from adjacent land (Mckay *et al.* 1970).

LESSONS OF HISTORY

Impacts of Climate Variations

Overcoming the difficult Arctic climate has challenged generations of explorers. The opening of the Arctic with European exploration and its subsequent exploitation occurred during periods of relatively benign climate. Iceland became a centre of western culture during climate-warming in the ninth and tenth centuries. Its fortunes shifted in phase with subsequent warming and cooling. Thousands of Icelanders emigrated during the cold spell that lasted from 1870 to 1918. As the climate warmed in the first part of the twentieth century, a major cod fishery (408,000 tonnes peak) opened in 1917 west of Greenland, to be drastically reduced in the 1960s as a result of cooling climate (Cushing 1979; Wallén 1986). Lamb (1985) has noted that the optimum temperature for cod is between 4 and 7°C: they cannot exist in water colder than 2°C. The opening of the Eastern Passage to the north of the Soviet Union occurred in the 1930s when warming reached a peak. Fears were expressed then should the climate revert to normal. Subsequent technological change has helped compensate for the extreme climate. Nevertheless the entrapment of the Soviet vessels in heavy ice north of Siberia in the winter of 1982-1983 demonstrated continuing vulnerability. Certainly the return to a colder climate reversed hopes for agriculture in the Kola Peninsula that were raised in the 1930s when many new plant species were introduced there (Kovda 1980). More recent cool intervals in the 1960s have also caused great stress in Iceland, reducing agricultural production (15% loss for 1°C cooling), displacing the herring fishery, and leading to currency devaluation (McKay *et al.* 1980). The importance of such climate variations must be kept in mind. However, another factor must also be considered - the possibility of climate-warming as a result of atmospheric changes caused by human activities.

THE SEASONS

Winter dominates the Arctic scene. Defined as that period when the mean air temperature remains below 0°C, it lasts over 300 days in northern Ellesmere Island and 275 days near latitude 70°N (Figure 2). Precipitation over much of the Arctic Archipelago is very light (Figure 3), heavier snowfalls occurring in those areas exposed to winds from open oceans. Snowcover and the relative absence of solar radiation contribute to the extreme cold and length of winter. Although cold, wind and drifting snow may curtail activity, winter is often the favoured season for travel since the ground is solid and ice covers the waters. The summers are cloudy and cold partly because of the extensive ice that covers the polar seas (Figure 4). Microclimates play a major role in plant growth that is needed for wildlife survival. Storms are rare in summer, and the weather is frequently clear and void of haze.

Temperature

January mean daily minimum temperatures average between -25 and -38°C, the coldest region being the M'Clintock Channel - King William Island area. The daily range is not great, averaging about 8°C. The cold is steady and intense, however, the moderating effect of the Arctic ice becomes readily apparent. The oceans exert a moderating influence on temperature, even through the sea ice, so that more extreme low and high daily values are found in continental areas to the south. Island winters do not produce the extreme low temperatures found in some more continental areas, such as Snag, Yukon where the temperature has fallen to -62.8°C. The winter cold is steady as noted in Table 2.

TABLE 2: MEAN DAILY TEMPERATURE °C

	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
Gladman Pt.	-23.6	-30.0	-34.7	-35.0	-32.2	-22.5
Mould Bay	-26.6	-31.2	-33.5	-35.2	-32.8	-24.1
Pond Inlet	-25.1	-28.4	-30.7	-32.7	-31.1	-21.7

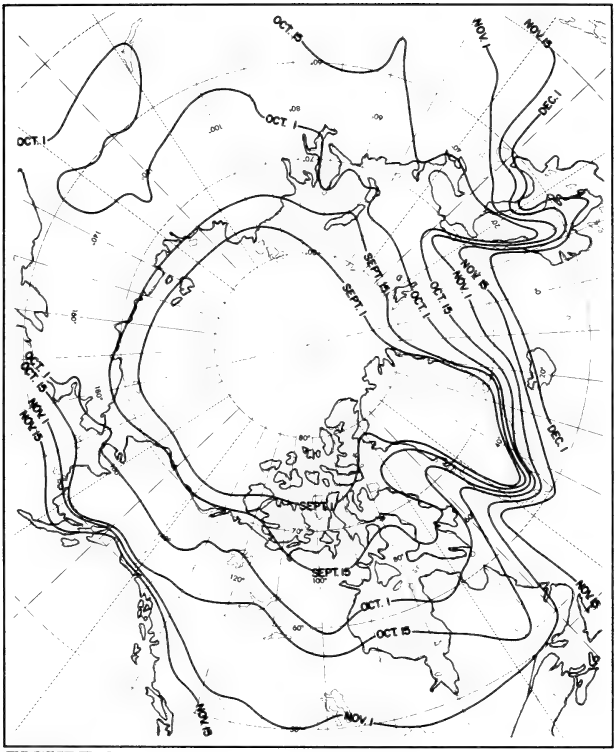

FIGURE 2: Date on which mean daily temperature falls below 0°C (McKay et al. 1970.

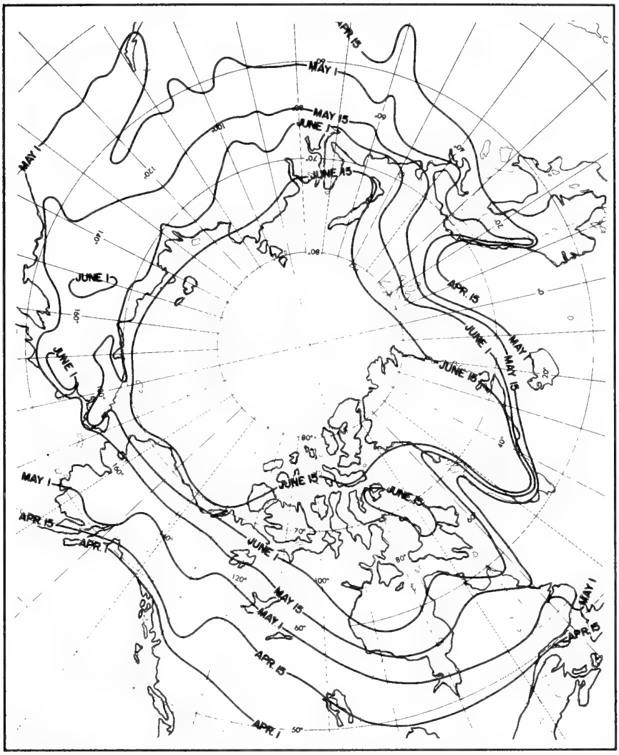

FIGURE 3: Date on which mean daily temperature rises above 0°C (McKay et al. 1970.

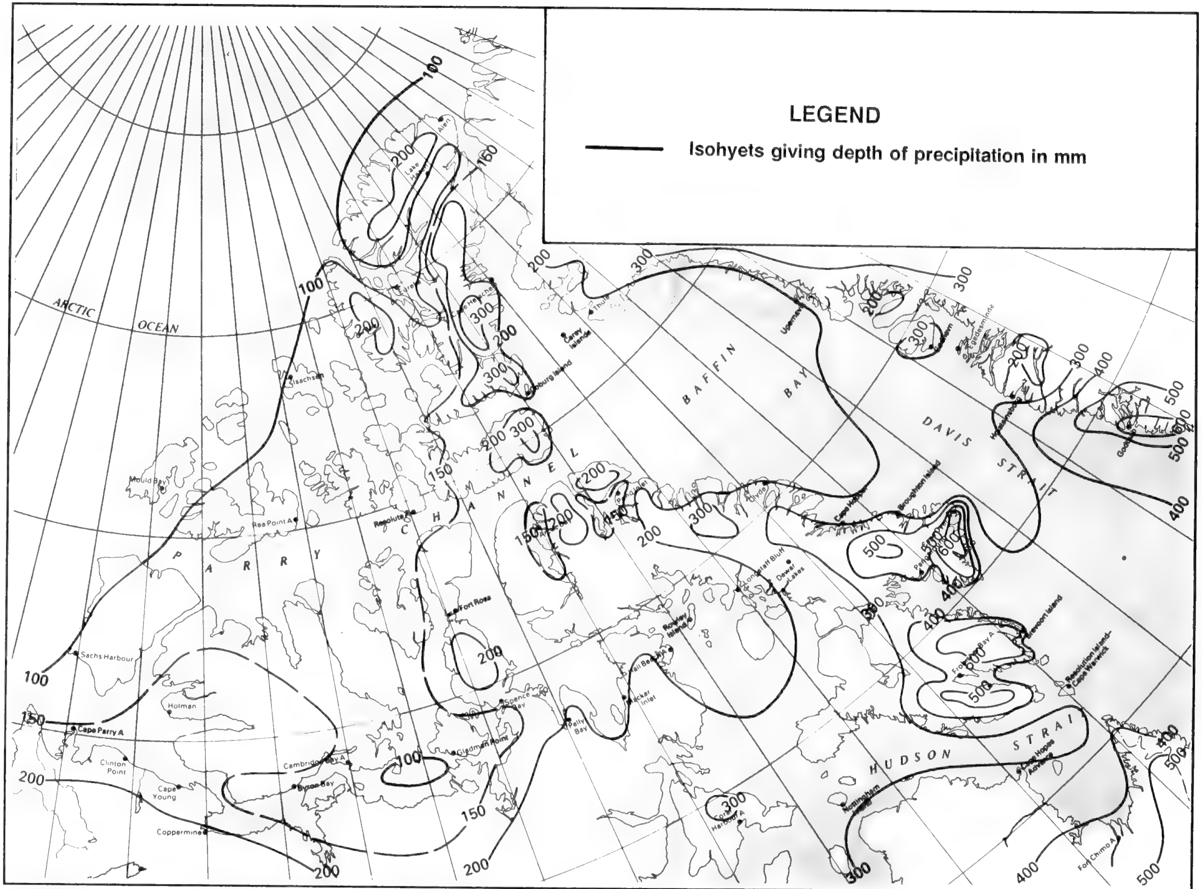

FIGURE 4: Annual mean total precipitation, 1941-1970 (Maxwell 1980).

TABLE 3: MEAN DAILY TEMPERATURE °C

	May	June	July	Aug.	Sept.	Oct.
Cambridge Bay	-9.4	1.5	7.9	6.5	-0.7	-11.7
Arctic Bay	-8.0	1.5	5.6	4.6	-1.7	-11.4
Eureka	-10.7	1.8	5.4	3.3	-8.3	-22.1

The 'free-air' mean July maximum temperatures average about 10°C in Victoria Island and southwestern Baffin Island to 5°C northwest of the Queen Elizabeth Islands. The mean July temperature 10°C isotherm roughly conforms with the mainland treeline. Across the islands the daily range averages about 7°C. With the disappearance of snowcover, temperatures rise inland from the marine ice fields, and maxima have reached 29°C at Cambridge Bay, 24°C at Frobisher Bay and 19°C at Eureka.

Over land covered by ice sheets, no months of the year have mean temperatures above freezing, and there is no significant diurnal range of temperature. Lowest temperatures occur at the end of the dark period. Melting occurs a few days in summer.

Precipitation/Snow Cover

Most precipitation is due to cyclonic storms, but frost and rime also contribute to the accumulation. Snowfall is by far the most common form and snowcover the dominant feature. In addition to being a product of climate, snowcover also shapes the climate. Annual precipitation is generally less than 350 mm and is primarily due to cyclonic storms. Frost and snow occur in every month and snow covers the ground about 10 months of the year (Figure 5). Snowcover is hard, dry and quite variable in depth. It averages 30 cm depth inland, but a vast portion of the barren lands in Arctic Canada accumulate relatively little snowcover and are referred to as a polar desert. Snowcover has a vital role to play in protecting plants and rodents from the cold and winds as well as contributing to their water supply. On the other hand it is an obstacle to grazing caribou. The snow-depths increase toward sea coasts reaching about 300 cm on exposed mountain slopes.

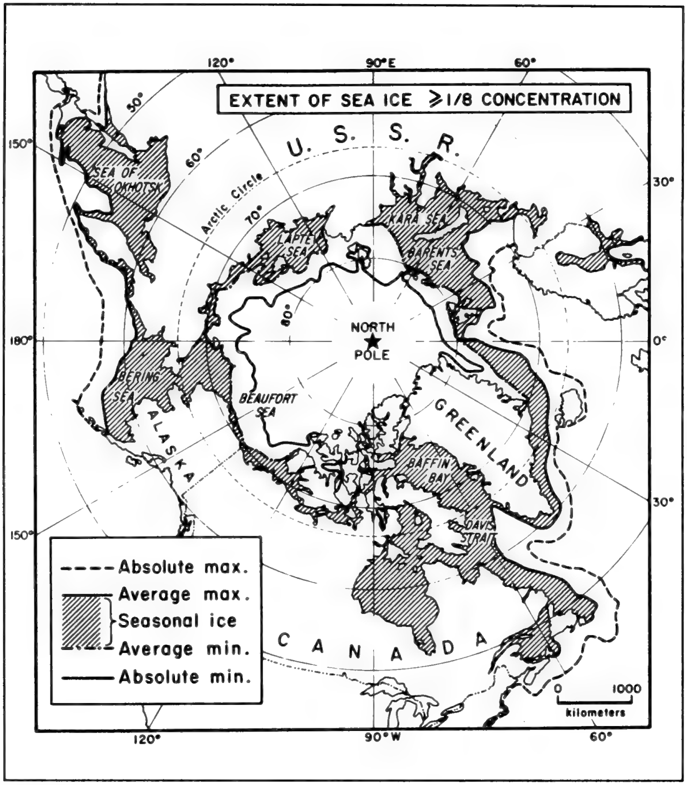

FIGURE 5: Mean and extremes of variable sea ice ≥1/8 concentration in the northern hemisphere (Barry 1983).

Storms

Storms are often severe near the coasts where supergradient winds may occur when extremely cold air comes in contact with the open ocean. There, snow and gales may frequently cut access to harbours and settlements and complicate travel in ice-fields. Winter storm winds in excess of 50 kts and gusts of over 100 kts are sometimes reported. Winds at Cape Hopes Advance were recorded in excess of 100 kts over a 5-hour period and averaged 125 kts over 1 hour in a November 1931 storm (Archibald 1969). Concurrent winds of 83 kts and a temperature of -30°C were recorded at Winter Harbour. Gales have driven seas inland, flooding low-lying areas, and strong winds have blown away buildings at Port Burwell and Alert. The combination of drifting and blowing snow under severe wind conditions threaten wildlife and humans alike. The presence of sea ice prevents or mitigates surge and high-waves.

Variability

Variability is a normal feature of every climate and, as noted above, the Arctic is no exception. There are marked variations in climate from season to season and year to year. Interannual and long-term variability is even more marked than that found to the south. Warming in the early part of this century was much more intense in the Arctic than the South. The variations in climate are reflected in the extent and thickness of sea ice, the formation and melting of which is highly correlated with air temperatures. As in the South, the extremes of climate are of great importance. The severely-cold winters cull out less hardy biota and critically test human designs and structures. For example, exceptionally deep snowcover over nesting grounds resulted in large losses of geese in 1972. Unusual drought, winds, snowcover, ice-storms and thaws have all taken their toll.

ATMOSPHERIC CHANGE

The climate of the Arctic has changed dramatically over time. The fossil dawn redwoods of Axel Heiberg Island, ice-covered peat on Ellesmere Island, and driftwood found on raised beaches in Greenland and surrounding Hudson Bay attest to dramatically different climates in the past. The noted opening of the Eastern Passage north of the Soviet Union

and the rise and decline of the cod fishery off west Greenland give evidence of notable short-term changes within recent history. Climate projections for the future introduce a new dimension because of dramatic alteration of the chemical composition of the atmosphere as a result of human activity. Historically the effects of man have been local. Now they have become a global issue of much concern.

Chemical Change

The climate-system is gradually being transformed by human activities. Most notably, the atmosphere has been used as a sump, receiving and transporting chemical emissions from a wide range of industries. Major contaminants include CO_2, CFCs, CH_4, SO_x, NO_x, other radiative gases and emissions that contribute to acid-rain and tropospheric ozone as well as toxic depositions. These emissions have led to major atmospheric changes manifest in acid and toxic depositions and in the ozone hole over Antarctica. Add to those effects the implications of greenhouse-warming, arctic haze, desertification and other massive land-use changes, and the assault on the climate-system is seen to be enormous - with major implications for the Canadian Arctic Islands.

The relative absence of precipitation-scavenging (liquid and solid precipitation are highly effective in removing air pollutants) and the existence of strong atmospheric inversions have been blamed for the net accumulation of pollutants such as sulphates, mercury, cadmium, vanadium and manganese in the Arctic. Their sources are primarily the industrialized areas to the south. The pollutants, along with particles from other land and oceanic sources, form an "Arctic Haze", which is widespread and well-mixed. The concentration shows strong seasonality, the winter peak attaining levels that are 20 to 40 times greater than in summer. The haze is acidic, being about 30% sulphate, but the levels of acidity are still 10 times lower than in industrialized areas to the south (Rahn 1980). Arctic pollution can be exacerbated locally (e.g., emissions at airports). That pollution, too, shows strong seasonality, and depositions can be episodic depending on precipitation, boundary-layer wind speed and direction, and the duration of stagnant periods. Both local pollutants and those transported over long distances alter the reflective and radiative properties of the snowcover and the atmosphere. Since the ground is snow-covered most of the time, there is little convection and ventilation is poor in the absence of storms. Pronounced inversions that persist all day in valleys, coupled with the incapacity of the cold air to hold significant quantities of

moisture, can result in locally intense concentrations of pollutants and increased frequencies of ice-crystal fogs.

The "Greenhouse" Effect

Much has been written and said of warming of the Arctic due to the so-called "greenhouse" effect. Is it real? In 1979 the U.S. Academy of Sciences stated: "we have tried, but been unable to find any overlooked or underestimated physical effect that could preclude the currently estimated global warming due to a doubling of CO_2 .... We cannot exclude the possibility of some mitigating effect – but, nor can we exclude the possibility of more continuous and drastic changes." (U.S. National Research Council 1979).

Many gases contribute to the "greenhouse" effect. Most widely recognized is CO_2 which has increased from about 280 in 1850 to about 350 ppmv at present. CFC 11 has increased from zero to 0.24, and CFC 12 to 0.42 ppb over their period of use. The increase in methane is accredited in part to increases in populations of cattle, the cultivation of rice, and other land-use changes that show no signs of reversal.

There is now widespread acceptance that global climate has already warmed about 0.5°C as a result of human activities and that a 3°C warming (about $4W/m^2$) is possible within the next 70 years. The warming effect will be amplified at high-latitudes due to the strongly positive feedback effects to albedo alteration as the duration and area of snowcover diminishes, and as a result of modification of the marked atmospheric temperature inversions found in the Arctic (reduced vertical mixing of increased warmth). The greatest warming would be in winter, January surface-warming being about four times that of the tropics. Much of the additional summer thermal energy would be used in melting snow and ice, and stored in the surrounding ocean. The release of the stored heat from the ocean and the heat of fusion would contribute to moderation of winter temperatures. Extensive cloud might prevail in summer, reflecting incoming solar radiation in much the same manner as snowcover - a factor that requires closer investigation. Much increased precipitation is expected, and that too could complicate projections for some areas. Ice sheets might increase, and the snow-free period be relatively unchanged in those areas experiencing significantly increased snowfall and increased cloudiness.

CONSEQUENCES OF CHANGE

Rough estimates of response to climate can be made for biomass production, duration and thickness of ice-cover, duration of the growing and ice-free season, etc. The following are very generalized speculations on the consequences of such projected changes. They are based on indicated changes in the annual means of climatic parameters. Admittedly seasonal values could be superior, but their subjective nature makes more detailed projection unwarranted.

Climatic analogues (Figure 6) and regressions involving climate-parameters were used by McKay and Baker (1986) to assess the effects of a warming of about 2°C in summer and 10°C in winter. The regressions indicated that:

(1) biomass production approximately doubles for every 10°C increase in mean air temperature assuming no moisture constraint (Lieth 1973).

(2) the mean annual position of the edge of the sea ice tends to follow the 0°C isotherm of annual mean daily air temperature.

(3) the peak thickness of ice is largely a function of air temperature and can be estimated using degree-day techniques. Two-metre ice thicknesses are found with mean annual temperatures of about -16°C, and 1 m thickness with temperatures of about -2°C in regions that are unaffected by local phenomena.

(4) freeze-up and break-up dates of ice in bays and lakes are related to the annual temperature regime. Spatial variations generally reflect the mean annual temperature patterns, but marked exceptions occur near very large, deep-water bodies. The date of break-up tends to be advanced four days in spring and delayed three days in autumn for every 1°C increase in the annual mean daily air temperature.

(5) snowcover tends to disappear when the daily mean temperature reaches 3°C in spring, and to reform when the daily mean temperature drops below -0°C.

(6) the southern limit of discontinuous permafrost follows the -1°C annual mean daily air temperature isotherm; the edge of continuous permafrost the -8°C isotherm under present "steady" climate conditions. Warming of the permafrost would lag greatly behind atmospheric warming.

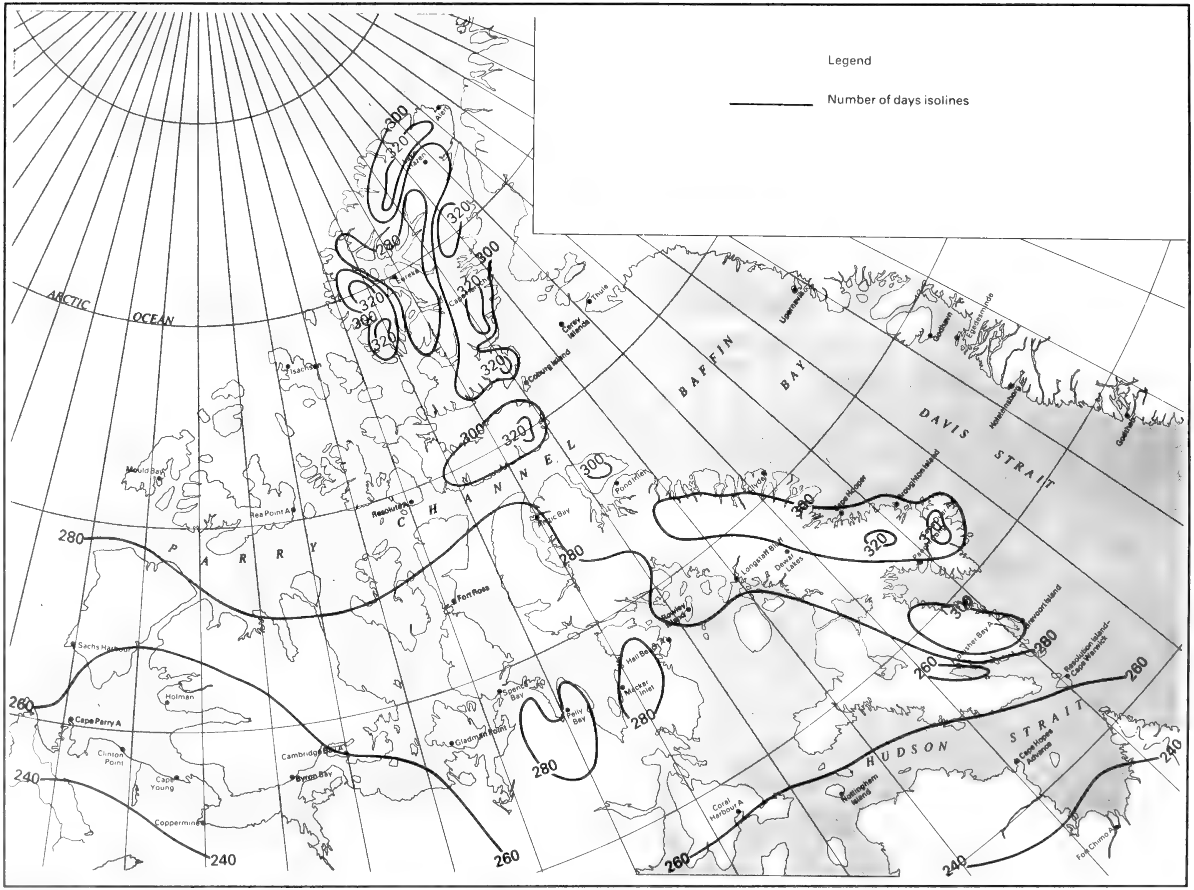

FIGURE 6: Mean duration of snowcover of at least 2.5 cm, 1955-1972 (Maxwell 1980).

The analogues are based on estimates of temperature and precipitation obtained using numerical models. They indicate a poleward migration of climatic isolines of about 1,100 km for a doubling of the concentration of atmospheric CO_2.

Marine Transportation

The most apparent physical effect of climate-warming is the reduction in coverage and thickness of sea ice. Navigation seasons could be extended by about six to seven weeks, and the peak thickness of ice reduced by about 20 cm by 2050. Should that occur, the warming process would be expected to continue and an ice-free Arctic is projected to follow - say by 2200. With the doubling of CO_2, navigation along the three access routes to the Arctic - the Mackenzie River, Hudson Strait and through Davis Strait and Baffin Bay to Parry Channel would be lengthened by one to two months. The Hudson Bay route would be open from early July to mid-November. At Iqaluit (formerly Frobisher Bay) the harbour would probably be clear of ice from mid-June to mid-November, at Resolute from early July to mid-October. The Davis Strait route would be open to small, unsupported craft for two and a half months compared to the present duration of a month. Both shipping and icebreaker operations would be facilitated by the thinner ice and shortened season. Icebergs and fog would continue to be major hazards along the route. Coastal shipping from the Mackenzie Delta and offshore drilling conditions would be significantly enhanced by the increase of about six weeks in the length of the navigation season.

Ice-cover would be general in winter, but less extensive in summer. It would be thinner and more easily traversed by strengthened ships. Transportation from the Pacific to the Atlantic via the North-West Passage could be much more feasible than at present. The reduction in pack and floe ice could make viable many projects that are now presently uneconomic. Similarly the opening of coastal areas for longer periods and with thinner ice could result in altered routings, port development, and less costly port and ship construction and maintenance. The reduced ice hazard offshore, warmer operating conditions and much improved sea transportation conditions would be a boon to the energy and mineral resources sectors. The costs of ice-breaking and constrained use for ships and facilities are part of the climate penalty. Some of the major energy fields are within the Queen Elizabeth Islands where ice-fields can be severe. But the actual result is unpredictable being

dependent on technology, geology and markets as well as climate. Assuming a favourable supply/demand situation, a warmer climate will enhance viability and profitability.

Another aspect of climate-warming is that sea levels will increase as the volume of the ocean waters expand. This poses the problem of increased coastal flooding. Inland, there would be a slow poleward migration of permafrost, and increased land-use problems due to thawing of the active layer.

Implications of Altered Access

Access to resources (oil, gas and minerals) and markets is of great economic importance. Overcoming climate and climate-related hazards contributes significantly, along with distance, to the cost of resource exploration, extraction and transportation. Operations and maintenance can be costly because of the remoteness of sites, routes that are encumbered by ice and snow, construction that is affected by permafrost, and the performance of materials, vessels, machines and people in extremely cold environments. An additional cost is that of stockpiling (inventory) - necessitated by the seasonal nature of transportation. Lengthening the shipping-season would reduce these costs and thereby increase the viability of many Arctic operations.

A related factor is the probability of greatly increased Arctic maritime travel (Figure 7). Several nations have shown their interest in using the North-West Passage for scientific, military and commercial travel. That interest would greatly increase given more favourable marine and climate conditions. The result would be a need for adequate docking facilities, port, vessel and environmental security, navigation aids, search and rescue and enforcement capabilities. Canada's responsibilities for the Northwest Territories would necessitate a much increased presence and control. The projected opening of the Arctic to travel would have negative effects as well, exposing native peoples to increased pressures from the south.

Interrelationships

A warming Arctic would have major implications for the regions to the south. This would be directly apparent in the tempering of "Arctic outbreaks" over southern Canada. The north-south temperature gradient would be diminished, resulting in fewer intense weather fronts in temperate latitudes and decreased winds. The ice free-season in Hudson Bay would be increased. The altered climatic regimes and runoff would similarly alter the

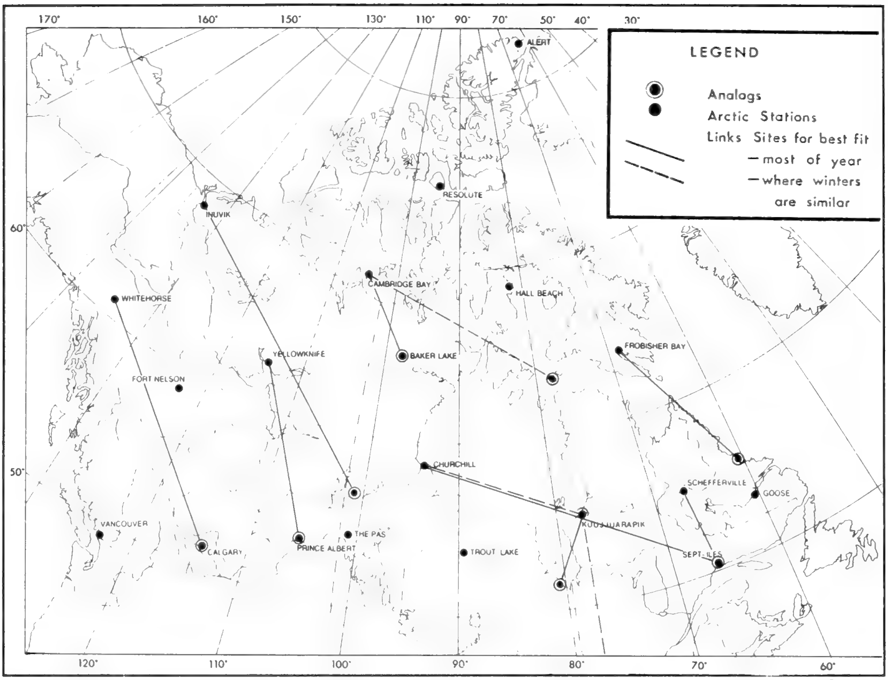

FIGURE 7: Present-day analogues of projected temperatures for northern Canada following a doubling of CO^2 in the atmosphere (McKay and Baker 1986).

character of estuarine and ocean currents - resulting in yet another array of positive and negative feedbacks of significance to the High Arctic. Much research is required before such changes can be considered as more than speculations; however, there is wide consensus that significant change will occur within the next 50 or 60 years. A much better understanding of the nature and consequences of such changes is a vital requirement for planning the future of the Canadian Arctic Islands.

CONCLUSIONS

(1) The Climate of the Arctic Islands is generally seen as cold and forbidding with winter dominating the scene.

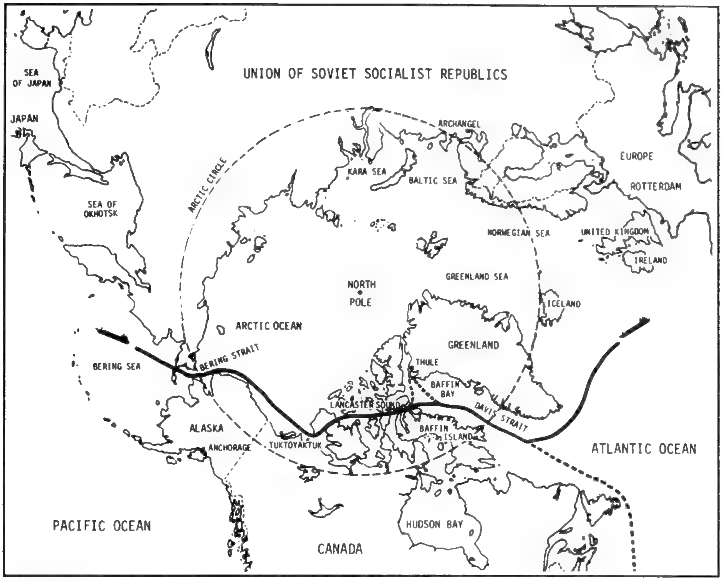

FIGURE 8: Arctic transportation routes (Burnet 1985).

(2) History discloses that the climate is variable and that changes at high latitude are greater than those experienced farther south. Furthermore, they show that climatic extremes are of critical importance for people and ecosystems. An altered climate will present a new set of extremes.

(3) Significant climate alteration may be in progress, and manifest itself clearly within a lifetime. This is likely because of chemical changes and radiative changes that affect the atmosphere. The projected effects of warming by such alteration are far greater that any recorded, and they could impose profound changes on people, ecosystems, and economies, having a major influence on maritime navigation, sea level, energy and mineral exploration, as well as plants and animals. Other changes due to chemical alteration are the depletion of protective stratospheric ozone and increased deposition of toxic chemicals and acidic ions. Their combined effects have profound implications for Arctic ecosystems and economies in the not-too-distant future.

(4) Much improved understanding of climate and of the way in which the land, sea and ecosystems respond to atmospheric and climate changes are needed in order to suitably plan for and adapt to such changes.

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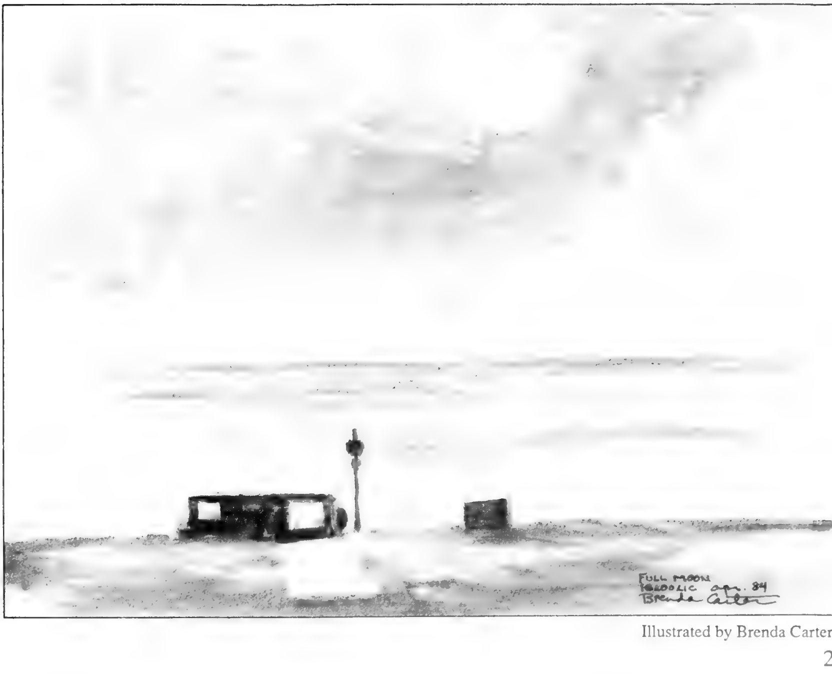

Illustrated by Brenda Carter

THE QUEEN ELIZABETH ISLANDS: A CASE STUDY FOR ARCTIC CLIMATE DATA AVAILABILITY AND REGIONAL CLIMATE ANALYSIS

Bea Taylor Alt[1] and Barrie Maxwell[2]

Abstract: The Canadian Arctic Islands provide a unique challenge in the collection and analysis of climate data. The degree to which this challenge is being met is examined by reviewing the extent and means of accessing climate data for the islands as a whole and through a case study of regional climate data analysis in the Queen Elizabeth Islands (QEI).

Access to the Atmospheric Environment Service (AES) climate database and to various "non-standard" data sets has changed dramatically during the past dozen years. Complex analysis can now be routinely carried out either on request, or by individuals themselves using AES-developed computer information systems such as: MAST (Marine Statistics), LAST (Land Statistics), DUST (Duration Statistics), CONAN (Contour Analysis), CRISP (Sea Ice Data Analysis), CLASP (Standard Climate Applications Statistics) and SPASM (Pressure Centre Movement Analysis).

The case study employs standard and non-standard climate data from the QEI to examine regional climate and climatic controls in this data-sparse area. The study underscores the importance of using appropriate time and space scales in climate-related studies. Regional summer climate patterns over most of the QEI result from the interaction of major topographical features with persistent northwesterly flow off the cold central Arctic Ocean. A distinctive "S"-shape is seen in mean monthly sea-level plots of most summer-climate parameters. July maps feature 1°C temperatures and 80% cloud-cover along the exposed northwestern edge of the islands compared to 8°C temperatures and 60% cloud-cover at the same latitude in the intermontane region of central Ellesmere Island.

Future climate work in the Canadian Arctic Islands will not only require use of technological advances in remote-sensing and automatic weather stations, but also careful, detailed analysis of the varied data now available and continued cooperation between all agencies and disciplines working in the area.

Résumé: Les îles de l'Arctique canadien représentent un défi pour la collecte et l'analyse de données climatiques. On examine le succès remporté face à ce défi en étudiant la portée et les moyens d'accès aux données climatiques pour ces îles dans leur ensemble et par une étude de cas d'analyse par région de données climatiques dans les îles Reine-Élizabeth.

Depuis environ 12 ans, il y a eu beaucoup de changements dans l'accès à la base de données climatiques du Service de l'environnement atmosphérique (SEA), et à divers jeux de données non standard. L'analyse complexe peut maintenant facilement être faite soit sur demande, soit par les intéressés eux-mêmes, à l'aide de systèmes informatisés mis au point par le SEA, comme MAST (statistiques marines), LAST (statistiques terrestres), DUST (statistiques de durée), CONAN (analyse de contours), CRISP (analyse des données de glace de mer), CLASP (statistiques d'applications climatiques standard) et SPASM (analyse du mouvement des centres de pression).

L'étude de cas fait appel à des données climatiques standard et non standard sur les îles Reine-Élizabeth pour examiner le climat régional et les facteurs influençant le climat dans cette partie du monde où les données sont rares. Elle met en relief l'importance d'utiliser des échelles temporelles et spatiales appropriées lors des études portant sur le climat. Les configurations régionales du climat estival sur la presque totalité des îles Reine-Élizabeth résultent de l'interaction des principaux accidents topographiques avec le flux persistant du nord-ouest venant du centre de l'océan Arctique, qui est froid. Les courbes moyennes mensuelles au niveau de la mer de la plupart des paramètres du climat estival montrent une forme en "S" caractéristique. Sur les cartes de juillet, on voit des températures de 1° C et une nébulosité de 80 % sur la bordure nord-ouest, exposée, des îles et des températures de 8° C et une nébulosité de 60 % à la même latitude dans la région intramontagneuse du centre de l'île Ellesmere.

Dans l'avenir, les études sur le climat dans les îles de l'Arctique canadien feront appel non seulement à la technologie avancée de télédétection et aux stations météorologiques automatiques, mais aussi à une analyse soigneuse et détaillée des diverses données présentement disponibles, ainsi qu'à une collaboration soutenue entre tous les organismes et disciplines oeuvrant dans le secteur.

INTRODUCTION

The Canadian Arctic Islands provide a unique challenge in the collection and analysis of climate data. The degree to which this challenge is being met is the focus of this paper. Climatological data available for the Canadian Arctic Islands and access to those

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data are briefly described. Emphasis is placed, however, on a case study of regional climate data and analysis in the Queen Elizabeth Islands - that portion of the Canadian Arctic north of Parry Channel (Figure 1). This case study underscores the importance of interpreting such data on realistic time and space-scales. The results also provide an opportunity to point out gaps in the existing climate data-gathering system and how these might be overcome.

Arctic Data Access

The Canadian Climate Centre (CCC), a component of the Atmospheric Environment Service (AES), is responsible for Canada's national archive of atmospheric data. This archive is quite diverse in terms of the types of information that are stored, the methods used to store them and the ways in which they can be accessed. All data collected at AES arctic stations are included and treated similarly to those from other regions of Canada.

Data stored in the archive for the Canadian Arctic are observed at stations which may be considered to belong to one or several of the different AES national networks (e.g. hourly and synoptic, daily climate, rainfall rate, sunshine, radiation, soil temperature, evaporation, upper air, freeze-up and break-up, snow survey, etc.) - the names suggesting the wide range of atmospheric and related elements observed in the Canadian Arctic. There are, however, wide variations in the density of arctic coverage within each network, and even where reasonable densities exist, there may be serious problems with representativeness of data. Arctic-station siting has often been more determined by logistical expediency than by optimal observing considerations. Currently, arctic climatological data are gathered commonly at manned stations, supplemented by automatic installations (some of which store data for later retrieval; others of which are capable of telemetering data for real-time use).

Table 1 provides an historical perspective on the development of the climate-observing network in the Arctic Islands, based on the AES Climatological Station Data Catalogue (AES 1981) for stations with digital data included in the national archive. For comparison, information on stations located at adjacent mainland coastal sites is included. The increase in numbers of stations resulting from the construction of the DEW line sites in the 1950s is evident. The decrease in the 1980s is a result of not only an upgrading of existing stations combined with the closing of nearby sites, but also a reduction in the number of oil and gas exploration sites whose data were put into the digital archive.

TABLE 1: HISTORY OF CLIMATE OBSERVING NETWORK[1].

[1] The number of stations in operation by decade are shown, both for stations exclusively in the Canadian Arctic Islands, as well as for sites along the adjacent mainland. The information is based on Atmospheric Environment Service station data catalogues and does not include stations operated by other government departments or by private industry.

	1880-1889	1890-1899	1900-1909	1910-1919	1920-1929	1930-1939	1940-1949	1950-1959	1960-1969	1970-1979	1980-	Total # Diff. Stations
Arctic Island Sites	1	1	3	3	8	15	19	39	43	43	29	67
Mainland Sites	0	0	1	3	4	4	6	28	28	19	16	34
Totals	1	1	4	6	12	19	25	67	71	62	45	101

As alluded to above, while a significant portion of the national climate archive is retained in hard copy or micrographic form, the majority of the data is stored digitally. Within the digital archive, data are generally organized chronologically as daily records of hourly values, monthly records of daily values, and/or annual records of monthly values.

Access to these arctic digital data is possible in three ways: publications, custom jobs or direct access. Publications range from long-term normals to routine weekly, monthly and annual summaries to special-purpose studies with specific applications. These are all generally available on request.

Custom jobs are needed when the user's specific requirement cannot be met with available publications. Several programs (general report programs - GRPs) and information systems have been developed to meet this need. The latter are collectively known as the MAST suite of systems, MAST standing for MArine STatistics. The systems originated with the need to access ship observations for evaluating offshore climate; however, with time, new components have been added to the original system so that data can be addressed and analyzed for land stations (LAST), for duration and extreme-value analysis (DUST), for sea-ice data (CRISP), for deriving synthetic winds for data-sparse areas (WISP) and for the movement of surface-pressure centres (SPASM). Contoured output from these systems is accomplished through another compatible system (CONAN).

The recognized need to allow direct access to the AES climate archive, as well as the requirement to address more efficiently its ever-increasing complexity, size and quality control,

aspects, resulted in the decision to develop a Climate Data Management System (CDMS). Objectives of the CDMS are: (1) to improve data capture; (2) to streamline quality-control; and (3) to allow access to current and archived data. When fully operational, this system will be easy to use, featuring online data entry, interactive quality, online check definition, document-tracking, reporting, archiving and data access. Integrated with CDMS will be a Station Information System (SIS) providing a complete record of station history (location, instrumentation, observing program and all changes).

An issue of particular concern for the Canadian Arctic and which is specifically addressed by CDMS is that of non-standard data (in effect, non-AES data). Until now, there was no policy that allowed for the integration of such information directly into the climate archive, so such data were dealt with on an ad hoc basis. This is a particular concern in the Canadian Arctic because, with data coverage that is generally sparse and of questionable representativeness in many cases, any additional data-gathering programs can be very valuable. Several specific data-sets provide good examples: the Polar Continental Shelf Project climate observations collected by scientific parties active during summer field-seasons (1972 on), regular weather observations taken by offshore operators in the Beaufort Sea during the summer-fall drilling season (1976 on), and data collected by the oil and gas industry at both land and on-ice sites at various locations in the Queen Elizabeth Islands (1973 on). At present, these are not technically part of the archive, but they are available in digital form as distinct data-sets which can be accessed through MAST.

THE QUEEN ELIZABETH ISLANDS

The Queen Elizabeth Islands (QEI) comprise that part of the Canadian Arctic generally lying to the north of 74°30'N (Figure 1). To the south, the QEI are separated from the rest of the Canadian Arctic Archipelago by Parry Channel, a broad waterway composed of M'Clure Strait, Viscount Melville Sound, Barrow Strait and Lancaster Sound. The northwestern edge of the Queen Elizabeth Islands, extending 1,450 km from southwestern Prince Patrick Island to northernmost Ellesmere Island faces the perennially ice-covered Arctic Ocean. The eastern QEI abut Greenland and its extensive ice cap across Nares Strait and northern Baffin Bay. In the northwestern and north-central QEI, sea ice fills the

inter-island channels even in summer. In the east, the channels are navigable in late summer.

Climate-data collection in the QEI has had an interesting history resulting in a rather diverse set of observing programs that generally continue to this day. At the root of this are three primary considerations: (1) the basic severity of the climate itself; (2) the remoteness of the area; and (3) the politics defining which government agency is responsible for what activity in the region. These bear strongly on the costs and locations of data-gathering programs. The result has been a wide range of data-collection practices (human vs. automatic, hourly vs. twice-daily, coastal vs. inland vs. offshore, long-term vs. short-term, year-round vs. seasonal, etc.). Although the Atmospheric Environment Service of Environment Canada has the main data-gathering responsibility, other agencies have been active including other components of Environment Canada and other departments such as Energy, Mines and Resources, Transport, Fisheries and Oceans, Indian and Northern Affairs, National Defence, Public Works and National Museums. Supplementing this has been increased private-industry involvement over the past few decades.

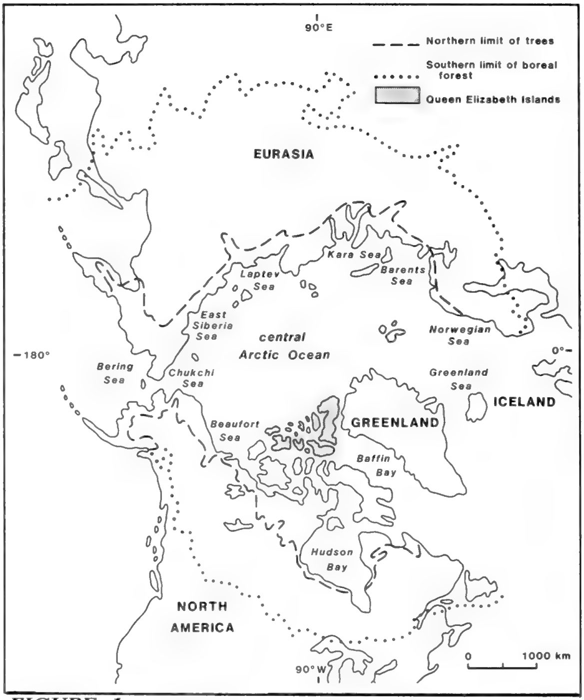

FIGURE 1: Circumpolar Arctic projection, showing the Queen Elizabeth Islands (shaded) within the Canadian Arctic Islands in relation to the Central Arctic Ocean and peripheral seas.

Climate Database

Climatological data for the QEI are available for a wide variety of locations, but as will be seen, the overall database has important limitations.

AES holds most of the data that are available in one form or another. The stations with the longest and most continuous records are the High Arctic Weather Stations (Alert, Eureka, Isachsen, Mould Bay, Resolute). Originally established in the late 1940s and early 1950s by Canada and the United States, these stations have been in continuous operation since, with the exception of Isachsen which closed in 1978. The duration and continuity of these stations (with the obvious benefits that such records offer for duration and extreme-value analyses) are, however, balanced by the fact that all five are situated at coastal sites. As such, their usefulness for inland or offshore applications may be limited, and any regional climate analysis based solely upon them should be approached with caution.

Other stations in the digital archive include: Craig Harbour, Bache Peninsula, Cape Herschel, Coburg Island, Dundas Harbour, Lake Hazen and Rea Point. These are all coastal locations, with the exception of Lake Hazen, but all are less useful than the High Arctic Stations for various reasons: short period of record, non-continuous record, non-contemporary data, high-elevation or local topographic concerns. Lake Hazen, although it provides the contrast of an inland site, has a continuous record over only one winter plus several summers in the 1950s.

The strong bias towards coastal data in the AES digital archive is balanced somewhat by observations gathered by scientific parties supported by the Polar Continental Shelf Project of Energy, Mines and Resources Canada. A scattering of inland sites is included in this database which is accessible through AES as a separate data-set covering the period 1973-1986. There are drawbacks to these data from the standpoint of length and continuity of record, as well as frequency of observation. For example, a typical station might operate for only one summer or part of the summer at a given location, and take only two observations per day at 12-hourly intervals. They can, however, provide insight into inland conditions, if only for a part of the year. This may be sufficient for certain applications such as vegetation studies. Figure 2 gives an indication of data-coverage during the summer.

While the impetus for the Polar Shelf data collection has been that of interest in related disciplines such as biological and terrain studies, a separate data-set has developed through the activity in the oil and gas exploration sector over the past 15 to 20 years.

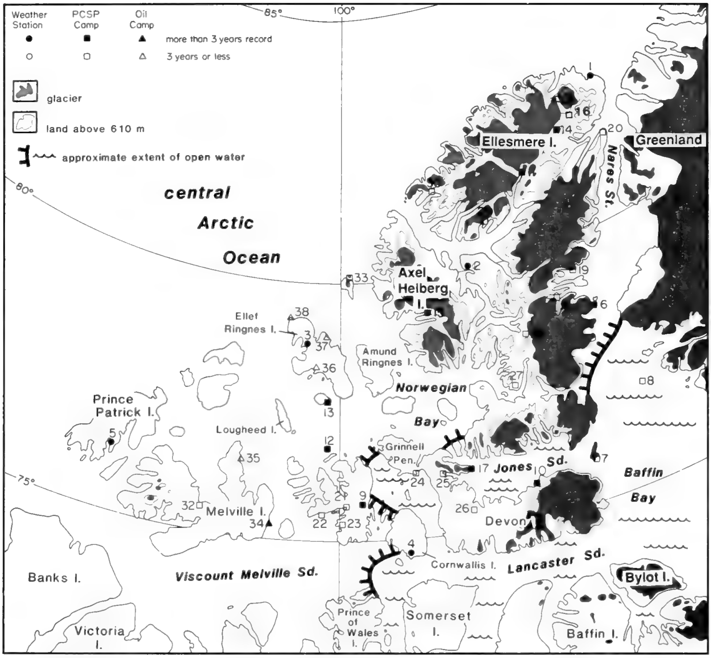

FIGURE 2: The Queen Elizabeth Islands: topography, modern glaciers and maximum extent of open water in a typical year (Maxwell 1982). Also shown are **Atmospheric Environment Service permanent weather stations**: 1. Alert, 2. Eureka, 3. Isachsen, 4. Resolute Bay, 5. Mould Bay; **Polar Continental Shelf Project** - supported, short-duration stations: 6. Cape Herschel, 7. Coburg Island, 8. Carey Islands, 9. Polar Bear Pass, 10. Truelove Inlet, 11. Tanquary Fiord, 12. Seymour Island, 13. King Christian Island, 14. Lake Hazen, 15. Expedition Fiord, 16. Piper Pass, 17. Cape Vera, 18. Alexandra Fiord, 19. Princess Marie Bay, 20. Judge Daly Promontory, 21. Bracebridge Inlet, 22. Bradford Island, 23. Hooker Bay, 24. Porden Point, 25. Eidsbotn Fiord, 26. Haughton River, 27. Baumann Fiord, 28. Strathcona Fiord, 29. Neil Peninsula, 30. Irish Arctic Expedition, 31. Clements Markham Inlet, 32. Nias Point, 33. Meighen North; **Oil Industry camps**: 34. Rea Point, 35. Drake Point, 36. Dome Bay, 37. Malloch Dome, 38. Cape Isachsen.

Among the QEI, such activity has included land-based drilling both at land sites and offshore from artificially strengthened ice-platforms during the winter. While these winter offshore data partially fill one gap in the regional climate-data coverage and the summer land-based data further supplement the Polar Shelf observations, the data-set as a whole suffers from its short-term nature: records rarely extend beyond a year at any site.

The QEI offshore area is not well served by climate-data collection programs outside the winter season. There has been increased marine transport activity in connection with the non-renewable resources, but it is usually concentrated in the surrounding waterways,

such as the Parry Channel or northwestern Baffin Bay, rather than among the islands themselves. Such data are also available from AES and accessible through MAST as discussed previously.

REGIONAL STUDY

The regional data-analysis presented in the following case study was originally developed to interpret the role played by climate in the observed patterns of plant distribution and diversity (Edlund and Alt 1989). However, it allows inferences to be made concerning other physical and biological environmental characteristics of the region.

The Problem of Scale

Climate and climate change operate on a continuum of time and space scales, from micro to global. It is impossible to separate this continuum into distinct scales; however, in order to address the complex problems of contemporary climatology (including climate change and its impacts on and interactions with the geosphere-biosphere), divisions of this continuum must be attempted. Barry (1970) has proposed distinct scales for the meteorological motion of systems and for spatial systems of climate. Hobbs (1980) tables the European, American and Japanese nomenclature for defining the variable atmosphere. Henderson-Sellers and Robinson (1986) have graphed the time and space scales of various atmospheric phenomena to illustrate the approximate linear relationship between the size of atmospheric features and their time-scales. Scale diagrams developed by Delcourt and Delcourt (1987) in their study of long-term forest dynamics include space and time 'domains' extending back in time to the origin of terrestrial vascular-plant life. Table 2 is a simplified version of the various approaches designed specifically for High-Arctic climate and climatically-sensitive processes.

Each scale of study has its own techniques, applications and problems. When studying climate-geosphere/biosphere interactions, all processes must be considered on the same time and space scale. A number of excellent continuing studies of microclimate and plant environment exist for the QEI (e.g. Courtin and Labine 1977; Freedman *et al.* 1983; Henry

TABLE 2: SCALE.

HORIZONTAL SCALE (KM)	SCALE	TIME SCALE	TOPOGRAPHY (EXAMPLE)	VEGETATION (EXAMPLE)	MINIMUM CLIMATE DATA (EXAMPLE: TEMPERATURE)	EXTENT TO WHICH THESE REQUIREMENTS ARE MET IN QEI
Global to 1000	Global	Decades Years Months	Ocean or continent (Polar Basin)	Ecosystem (tundra)	Surface and upper air grid values	Available on 381 km grid for several time periods
100 to 1000	Regional Synoptic	Months Days	Major topographic feature such as mountain range (intermontane region, Sverdrup Lowlands)	Vegetation zone (Herb Zone[3])	Network of surface and upper-air observations spaced to reflect major regimes	Upper air network adequate; surface network has gaps spatially and temporally
10 to 100	Meso	Days Hours	Valley complex, fiord complex (Truelove or Expedition Fiord study area[1])	Suite of plant communities on a soil catena (Range of plants on alkaline surficial materials through range of moisture)	Series of screen-level temperatures and one upper-air sounding	This type of data only available for limited time periods at specific research sites
1 to 10	Local	Days Hours	Small valley, plain or mountain-side (Oasis[2])	Plant community on one material and moisture regime (sedge meadow[3])	Several screen-level temperatures	As for meso-scale
< or = 1	Micro	Minutes Seconds	Single material or surface-type (beach ridge or snow patch)	Individual plant (Dryas)	Several levels up to screen-level at one site	General not available-particularly for this time scale

[1] Bliss (1977), Ohmura (1981)
[2] Freedman et al. (1983)
[3] Edlund and Alt (1989)

1987; Bergeron 1988). Meso-scale studies have been undertaken largely in conjunction with glaciological projects (Holmgren 1971; Ohmura 1981), although some oasis studies also reach the local scale.

This study focuses on the synoptic or regional scale - the time and space scale of a weather-system that is reflected climatologically by patterns of monthly normals (30 years). It requires a network of surface stations and several upper-air stations to define it properly. (Within the QEI, upper-air station coverage is adequate in this regard; however, at the surface, only four long-term continuous observing stations are operating, and they are all coastal). No comparable inland or offshore observing programs exist. Available data have been previously used (Maxwell 1980, 1982) to describe the region's climate in general terms.

Climate Controls

Climate is controlled by a complex interaction between the radiative energy reaching the top of the atmosphere, the inherent properties of that atmosphere, the motion of the atmosphere (atmospheric circulation), and the large and small-scale characteristics of the earth's surface. In the following case study, these complex climate controls have been approached in the following manner. Atmospheric circulation and its interaction with topography are discussed. The broad features of the solar-radiation regime are then examined and combined with atmospheric circulation to explain the main regional-scale climate patterns in the QEI. The extent to which these patterns can be defined from available data are then discussed.

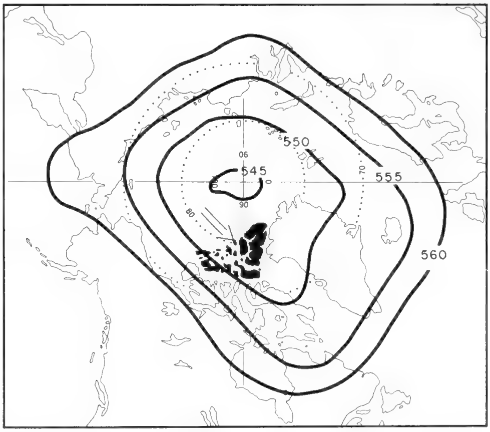

FIGURE 3: The 1948-1978 mean pattern of July 50-kPa height contours in decametres (dam). From Alt (1987).

Atmospheric Circulation

The summer atmospheric circulation is shown (Figure 3) by the mean July pressure pattern at 50 kPa (approximately 5,000 m ASL). The 50-kPa circulation is considered the

driving or steering-level for surface weather-systems and air-masses. With the exception of the east coasts of Ellesmere and Devon islands, the mean July flow is into the QEI from the central Arctic Ocean. This can also be shown by surface level streamlines which, when calculated from mean flow, show what trajectory a parcel of air would follow. Surface-streamline patterns for June and July (Figure 4) emphasize the predominant northerly or northwesterly movement of air from the central Arctic Ocean over the QEI.

Bryson (1966) pioneered the use of resultant streamlines to define the mean July position of the arctic front and related this to the position of the North American treeline. He also showed the results of tracing trajectories back to four external sources - Arctic, Pacific, and Atlantic oceans, as well as the United States. The frequency of occurrence of arctic air-masses over Canada for July, calculated by the trajectory method, is shown in Figure 5. The QEI lie within the 90% isopleth, and most of the western and central islands lie within the 100% isopleth. Although the results of Bryson's air-mass frequency analysis by the partial collective method (Bryson 1966) suffer from the low density of stations in the QEI, they show similar if less well-defined patterns.

Barry (1967) investigated the location of the continental arctic (cA) front by examining operational frontal-analysis charts for the 85-kPa level (Figure 6). His study showed that in July at 1,500 m over the QEI, an unmodified Ca air-mass occurs at least 80% of the time.

There is thus overwhelming evidence that in June and July, the QEI (with the possible exception of the east coast of Ellesmere and Devon islands) are dominated at all levels by air moving into the islands from the Arctic Ocean.

Topographic Controls

The interaction of the atmosphere and topography takes place at all scales (Table 2). In summer, the season considered here, the central Arctic Ocean is the coldest region of the northern hemisphere with a mean July temperature ranging from -1 to 2.5°C. The surface of the moving polar pack ice is extensively puddled, and this moisture source maintains a nearly continual, low-lying layer of stratus and stratocumulus cloud.

In the northeastern QEI, the mountains of northern Axel Heiberg and northern Ellesmere islands lie athwart the mean circulation, forming a barrier similar to (although not as extensive or as high as) the Cordillera in western North America (Bryson and Hare

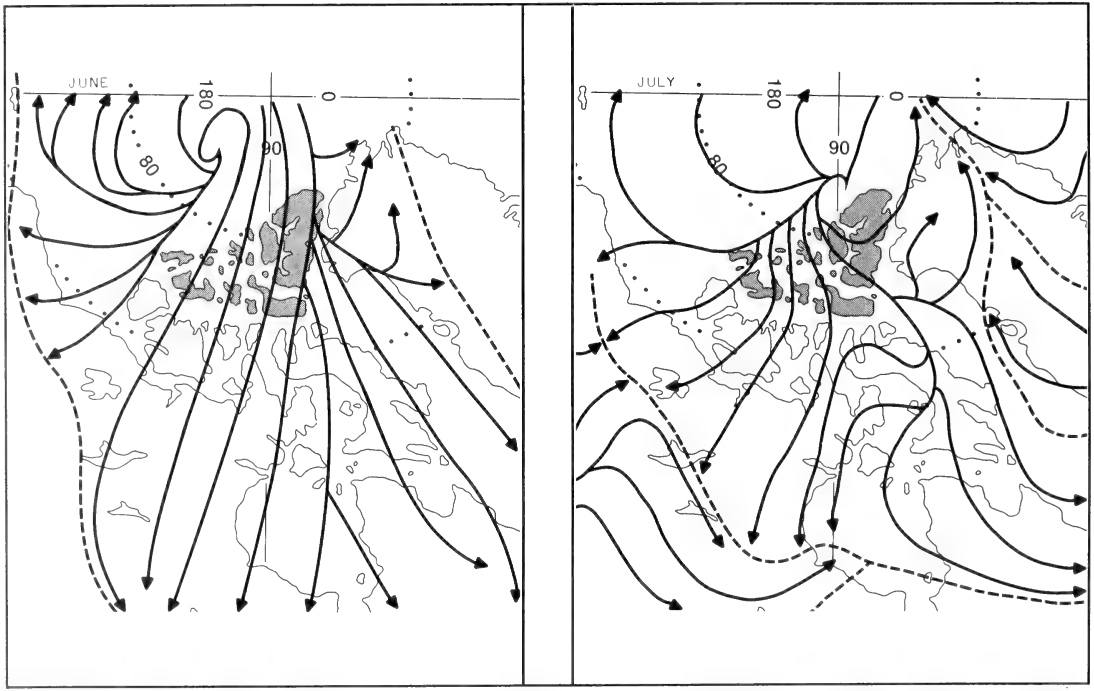

FIGURE 4: Surface streamline patterns for: (a) June, (b) July (after Bryson and Hare 1974). These represent the trajectories a parcel of air would follow.

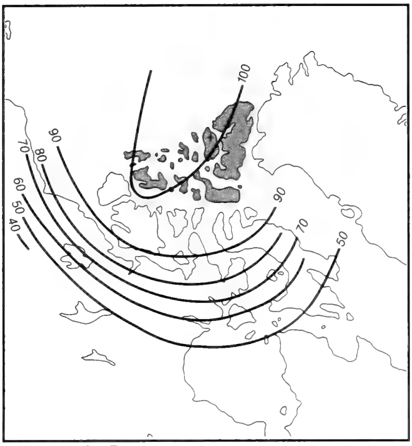

FIGURE 5: Frequency (%) of occurrence of air masses of "arctic origin" (after Bryson 1966).

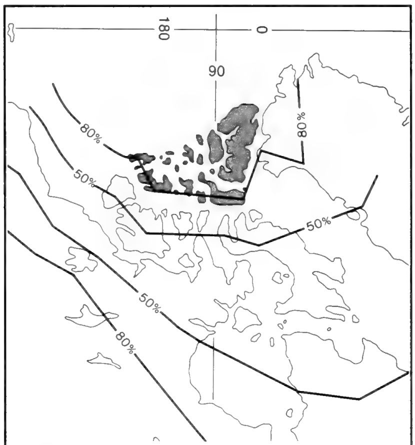

FIGURE 6: Frequency distribution of daily positions of the continental arctic front at the 85-kPa level for July 1961-1965 (modified from Barry 1967). North of the northernmost line, an unmodified arctic air mass occurs in the atmosphere 80% of the time at 1,500 m.

1974). The cold, moist Arctic Ocean air-mass (cA) is either deflected or lifted by the mountains. In the former case, the Arctic Ocean stratus and stratocumulus does not reach the sheltered interior region. In the latter case, the orographically-lifted air cools and precipitates much of its moisture; then it descends the lee-slope of the mountains with warming due to adiabatic compression and with decreasing relative humidity. It arrives in the Eureka Sound area (termed the Eureka Sound intermontane area; Figure 7) with dry, mild characteristics in contrast to the moistness and coldness of the Arctic Ocean air-masses (cA). A similar process of adiabatic-warming due to subsidence affects air entering the region above the central mass of the mountains.

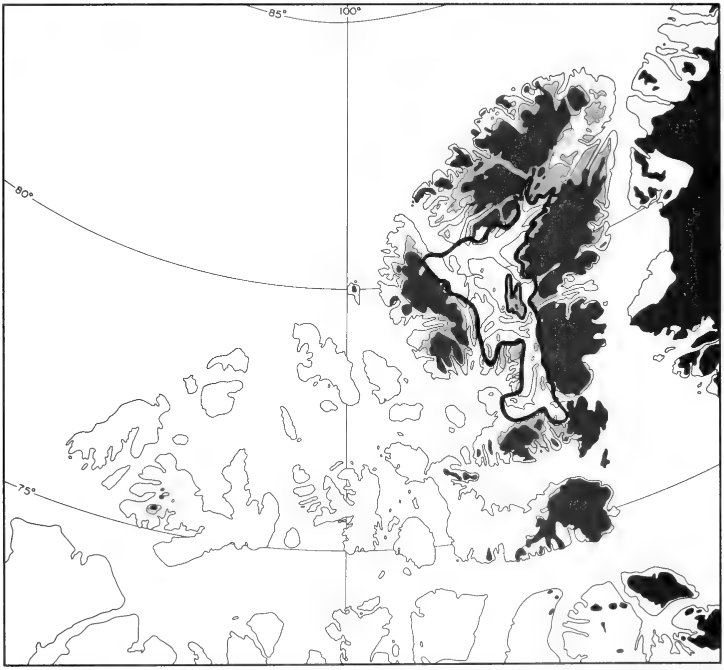

FIGURE 7: The Eureka Sound intermontane area (heavy outline). The small outlined area in the middle encloses the glacierized mountain ranges of eastern Fosheim Peninsula, which is not strictly speaking an intermontane area. The Sverdrup Lowlands comprise low-lying parts of the central and western QEI.

These warming processes are observed whenever the prevailing atmospheric flow is forced to cross mountain ranges (Flohn 1969). On a regional scale this results in a belt of precipitation on the windward slope, while the leeward side of the mountains is characterized by dry conditions. At the local scale, intense and sometimes isolated occurrences of warm dry winds in the lee of topographic barriers have been observed globally. These occurrences are often associated with specific synoptic conditions. In the Alps these winds have been known for centuries as 'Foehn'. Similar in effect but differing somewhat in extent and synoptic properties are the 'Chinook' (east of the Rocky Mountains), the 'Zonda' (in the Argentine Andes), and the dry winds in the eastern lowlands of southern New Zealand. The extent, frequency and synoptic nature of such situations in the Eureka intermontane region have yet to be studied, but are doubtless a feature of the area.

Similarly, the Eureka Sound intermontane area is protected from the extensive cloud and fog associated with synoptic systems moving up Baffin Bay and past the Victoria and Albert range to the east and the extensive mountains to the southeast.

This interior intermontane area is a regional-scale feature (Table 2), approximately 400 km long and 120 km wide (Figure 7). In its maximum extent, it is similar in size to the Columbia Basin in the northwestern United States or the Nechuka Plateau between the Coastal Range and the Rockies in British Columbia. Smaller areas on the scale of Alpine valleys (e.g. the Valais area of Switzerland (Wallén 1977)) can also be identified.

Distinct from the intermontane area, the central and western QEI experience cA air, which penetrates deeply the Sverdrup Lowlands. Over the sea ice of the inter-island channels, the air-mass undergoes little modification. The ice-bound islands of the Sverdrup Lowlands produce only local and meso-scale orographic uplift. This, coupled with the low stratus-stratocumulus cloud deck from the Arctic Ocean, results in frequent fog and low ceilings along exposed coasts. Inland, local and meso-scale thermal modification occurs through a shallow layer of the atmosphere. At times, the modification is deep enough to burn off the low-level cloud. The synoptic-scale nature of the air-mass remains, however, essentially unchanged.

Solar Radiation Regime

Solar radiation provides the energy to run the atmosphere. Unfortunately, observations of solar radiation and of radiation-balance in the Arctic Islands are sparse, records often being broken and of short duration. The observations that do exist suffer from a number of serious problems (Holmgren 1971; Dahlgren 1974; Maxwell 1980; Ohmura 1981). Published normals from the five AES stations do not adequately represent the relative values for these stations as there are missing years in the record. For example, there are only three years of simultaneous July records for all stations during the 1951-1980 normal period. Calculations of the radiation components, such as those of Vowinckel and Orvig (1962) or those used by McKay and Morris (1985), depend on the accuracy of the model and require accurate measurements for calibration. The values given in Table 3, however, allow a few important generalities to be made regarding the summer radiation regime of the QEI.

TABLE 3: *JULY MEAN DAILY SOLAR RADIATION COMPONENTS.*

STATION	Global Radiation ($MJm^{-2}d^{-1}$)				Surface Albedo	Global Radiation Absorbed ($MJm^{-2}d^{-1}$)			
	From Measured Values					From Measured Values			
	Average of 1971, 1972 and 1977[1]	Published Normals[2] (No. of Years)	Specific Years	Calculated Values	Measured (Estimated)	Average of 1971, 1972 and 1977[1]	Published Normals[2]	Specific Years (Year)	Calculated Values
Resolute Bay	19.0	18.7 (23)	16.4 (69,70)	18.0[4]	.39[2]	11.6	11.6	10.0 (69,70)	11.0
Resolute Bay			16.3 (73)					10.0 (73)	
Resolute Bay			16.9 (74)					10.3 (74)	
Eureka	19.4	18.8 (11)	18.6 (80-84)		(.15)	16.5	16.0	15.8 (80-84)	
Alert	18.4	18.8 (16)		18.4[4]	(.15)	15.6	16.0		15.6
Isachsen	16.5	16.9 (8)			(.45)	9.1	9.3		
Mould Bay	18.5	17.4		17.7[4]	(.45)	10.2	9.6		9.7
80 N 100 W				19.7[3]	.45[3]				10.8
80 N 80 W				22.1[3]	.45[3]				19.9
75 N 100 W				18.6[3]	.45[3] (.10)[8]				10.3
Expedition Fiord			15.4 (69,70)[5]		.10[5]			13.9	
Devon Base			18.8 (61,62)[6]		.15[5]			16.0	
Coburg Island			22.6 (73,74)[7]		.13[7]			19.7	
Carey Islands			18.5 (74)[7]		.13[7]			16.1	
Alexandra Fiord			19.4 (80-84)[9]		(.15)			16.4	
Thule AFB		20.5			(.15)		17.4		
Edmonton		21.9 (14)			.17		18.1		

1 The only three years of simultaneous records at QEI stations for July were 1971, 1972 and 1977.
2 Atmospheric Environment Service 1982.
3 Vowinckel and Orvig 1962.
4 McKay and Morris 1985.
5 Ohmura 1981.
6 Dahlgren 1974.
7 Muller et al. 1975.
8 Albedo estimated for land areas such as Fosheim Peninsula, not including ice caps.
9 Henry 1987.

In May, June and July, solar radiation reaching the top of the atmosphere at 80°N is greater than at any lower latitude, owing to the 24 hours of daylight. Radiation reaching the ground (global radiation) is strongly dependent on cloudiness. Under clear-sky conditions, the global radiation received at 80°N is greater than that received at 70°N along the mainland coast. Average global radiation values from permanent weather stations in the QEI for July 1971, 1972 and 1977 (the three years of simultaneous July records mentioned above) show a maximum at Eureka and a minimum at Isachsen (Table 3). The calculations of Vowinckel and Orvig (1962) show a minimum of global radiation west of Mould Bay and Isachsen over the Arctic Ocean. Though the actual magnitude of the difference in incoming global radiation between the Sverdrup Lowlands and the Eureka Sound intermontane area cannot be established due to instrument and missing-data problems, it is important to note that it is of the same order as the difference between Vancouver and interior British Columbia.

The reflective property (albedo) of the surface determines how much global radiation is actually absorbed by the ground. Measurements of surface albedo (Table 3) are available for Resolute and several expedition sites (Holmgren 1971; Dahlgren 1974; Alt 1975; Müller *et al.* 1976; Courtin and Labine 1977; Ohmura 1981). The following generalizations regarding regional albedo can be made.

Snow remains on the ground throughout June in the central and western QEI and at high elevations in the mountains of Ellesmere and Axel Heiberg islands. Thus, these regions have a high albedo. At Expedition Fiord and in other interior valleys of western Axel Heiberg Island, snow disappears by mid-June (Ohmura 1981). Snow disappears even earlier in the Eureka Sound intermontane area. Thus, the low albedos in June enhance the total energy absorbed in the interior area, while high albedos reduce the absorption of available energy over the sea ice and snow-covered areas in the northwestern portion of the islands.

By July, most of the land in the QEI is snow-free. Albedo differences between the Eureka Sound intermontane area and the Sverdrup Lowlands are less pronounced; however, differences in the surficial materials, vegetation-cover and moisture-content of the ground still result in enhanced absorption in the intermontane region and reduced absorption in the exposed lowlands.

In both months, therefore, the gradient of solar radiation absorbed at the ground is not latitudinal. Rather, the highest values are in the interior of Ellesmere and Axel Heiberg islands, and the lowest values west of Isachsen and Mould Bay over the pack ice of the central Arctic Ocean.

Summer Climate Patterns

Introduction

To examine how the distinctive climate regions produced by the interaction of solar radiation, general circulation and topography are reflected in regional summer patterns of temperature and precipitation, it is necessary to construct regional patterns of these parameters. In the QEI, this task is complicated by two serious problems: (1) the lack of adequate long-term stations and the representativeness of the existing stations; and (2) the complex mosaic of surface-conditions occurring in the islands. Surface-conditions within the islands and adjacent waters include: snow-covered mountains, ice caps, valley glaciers, snow-free rocks, bare ground, well-vegetated terrain, sea ice and open water. Several of these features often occur within a few square kilometres. So it is impossible to draw definitive maps of regional-scale parameters. However, in response to the needs of regional-vegetation studies (Edlund 1986) and to other studies of the physical and biological environment, we present regional maps of selected summer-climate parameters in as much detail as the data allow and in a form that meets the needs of regional-distribution studies. See Maxwell (1980, 1982) for comprehensive traditional treatment of the climate of this region.

Lower Troposphere

The interaction of circulation and topography is clearly portrayed in the mean June and July cloud-charts (Figure 8a,b). The prevailing northwesterly tropospheric flow drives the extensive stratus and stratocumulus cloud from the central Arctic Ocean into the Sverdrup Lowlands. Over the Eureka Sound intermontane region mean cloud amounts are 20% lower than over coastal areas bordering the polar pack. The satellite photograph (Figure 9) shows a typical example of these cloud conditions.

The same factors are apparent in the distribution of lower-troposphere temperatures as shown by July 90-kPa temperatures (Figure 10). Topography was not taken into account

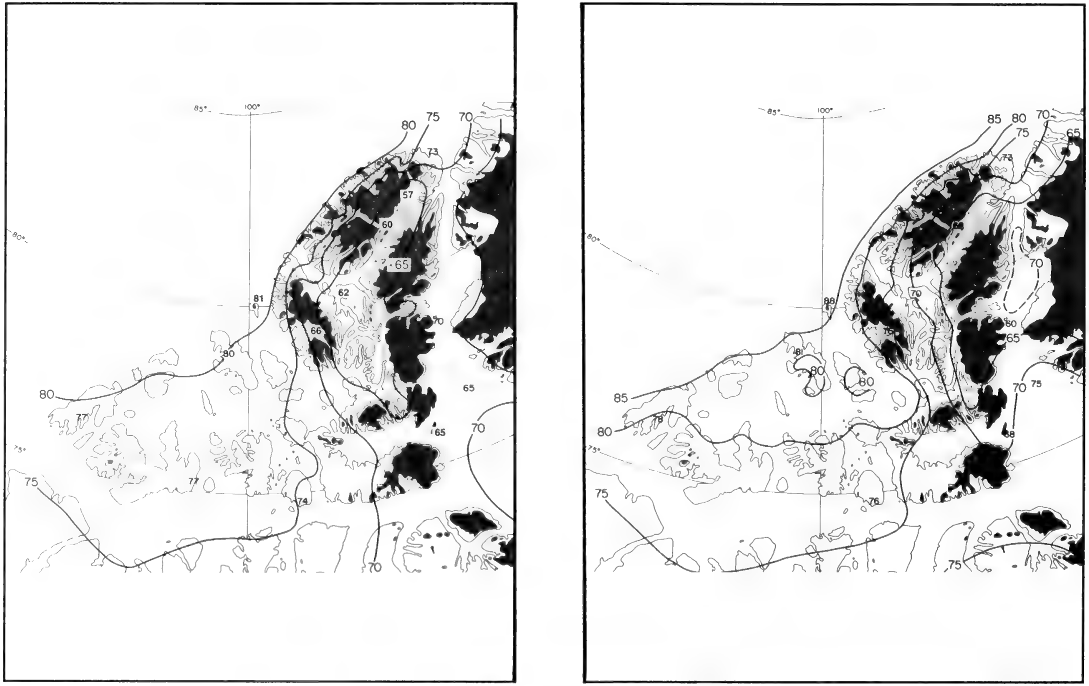

FIGURE 8: Mean cloud-cover (%) for (a) June and (b) July based on the period 1959-1979. Where applicable, field-station data were used (corrected as discussed in caption for Figure 11).

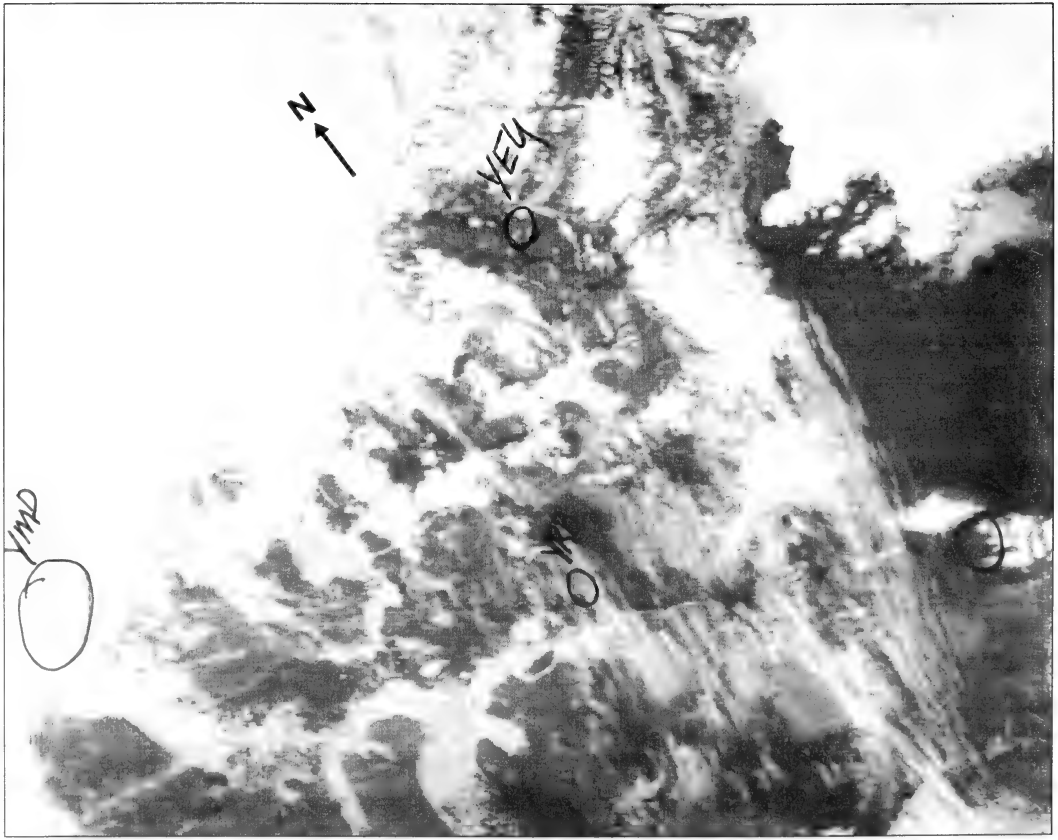

FIGURE 9: A typical example of cloud conditions over the Queen Elizabeth Islands during northwesterly flow. Image received by Geological Survey of Canada at Resolute from the Soviet METEOR weather satellite. Approximate positions of Mould Bay ("YMB"), Resolute ("YRB"), Eureka ("YEU") and Igaluit ("YIQ") have been marked.

when drawing the contours. These were spaced and shaped as demanded by the values of the five data-points alone. The intrusion of cold Arctic Ocean (cA) air over the Sverdrup Lowlands and the sheltering effect of the mountain barriers in the east form an S-shaped pattern similar to the cloud-patterns. This general S-shaped pattern is thus a macro or synoptic-scale phenomenon, reaching at least 1,000 m into the atmosphere and reflecting the impact of regional-scale topography on the lower troposphere.

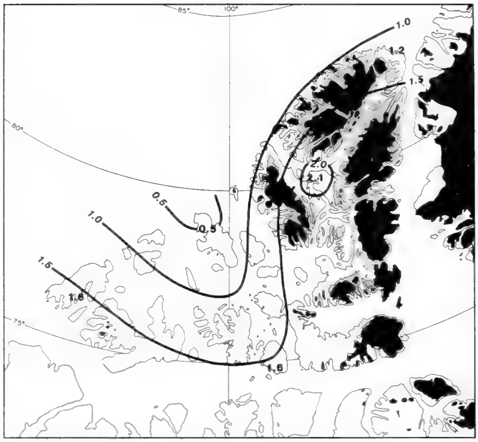

FIGURE 10: Mean July temperature at 90 kPa (ca. 1,000 m) for 1951-1980.

Temperature

The sparse surface-data network was augmented by incorporating information from seasonal scientific and oil-industry camps (Figure 2). Only stations for which a whole month (July) of daily mean records existed were used. Each monthly mean value for each year was adjusted to represented a 1951-1980 normal. The deviation from the 30-year normal at the closest permanent station(s) was used to adjust the monthly mean values from each field station. Values for the individual years were then averaged, resulting in a 30-year normal equivalent value. This method must be considered a first approximation as it neglects some important items, such as the fact that the normal period used was 1951-1980, while many of the years with data were in the 1980s.

Even with the addition of the field-station data (Figure 11), the interiors of the islands are virtually unrepresented. This is also true of the stations in the Eureka Sound intermontane area, most of which are on fiords or lakes. This problem has been used to advantage by plotting sea-level maps of both temperature and precipitation. The contours have been drawn through sea-level coastal station values. For any contour there are a range of values. For instance, in summer the lowest values would be found over the ice-bound channels and the highest at sheltered interior sites. Inland contours have been drawn only when they represent regional-scale features (i.e. 100 km or greater in size). Contours

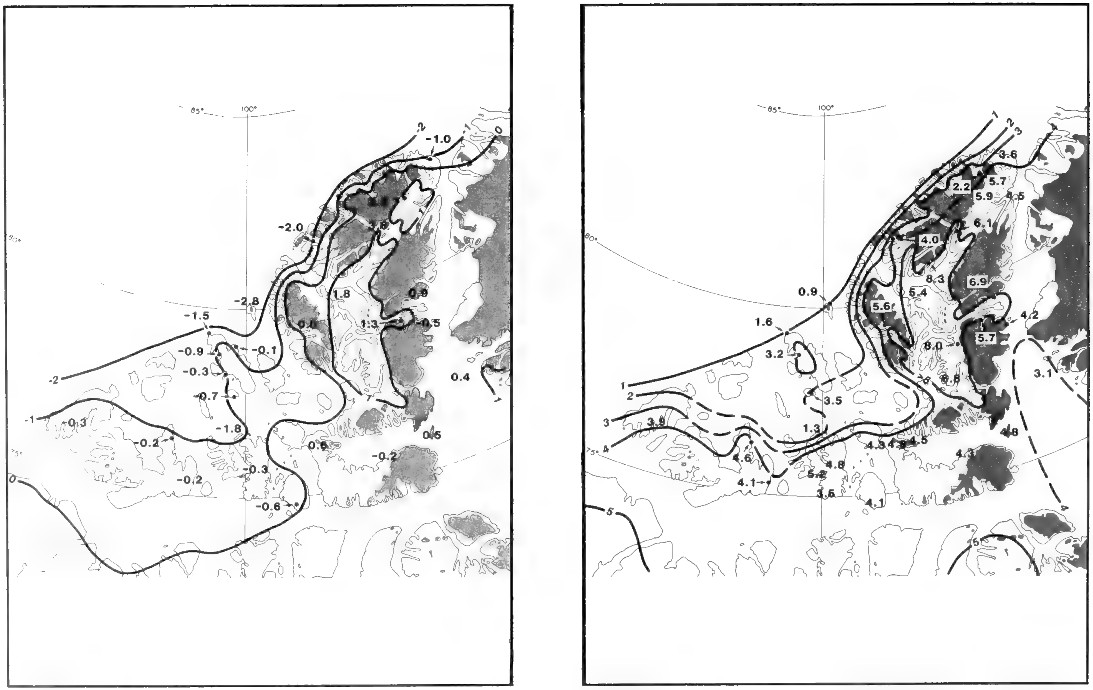

FIGURE 11: Mean monthly summer temperatures (°C) over the Queen Elizabeth Islands for: (a) June, (b) July. Permanent weather stations and non-standard weather data were used. Correction factors, developed through comparison with the appropriate permanent weather station records, were applied to the short-term record to produce values for the 1951-1980 normal period.

have not been drawn in mountainous areas (over 600 m, light-shading on maps) or over ice caps (shaded on maps). In drawing details of the contours, consideration was given to common sea-ice patterns and boundaries.

July (Figure 11b) temperatures at 80°N over the Sverdrup Lowlands are 4°C colder than similar coastal stations in the Eureka Sound intermontane area, whereas in June (Figure 11a) the 0°C isotherm separates the two areas. A relatively steep temperature-gradient exists over northern Ellesmere and Axel Heiberg islands which broadens in the Sverdrup Lowlands as the cA air-masses are gradually modified by increasing exposure of land.

In the intermontane area, coastal temperatures in July are greater than 5°C. Indications are that, inland, the temperatures are considerably warmer, although accurate long-term data are not yet available. Several field projects, begun in 1988, will eventually provide an accurate quantitative evaluation of inland temperatures.

In the Sverdrup Lowlands (Figure 7), the Isachsen and King Christian Island (KCI) (Figure 2) temperatures seem higher than those from other coastal stations. In the case of Isachsen, the site is somewhat sheltered. The KCI temperatures cause a sharp bend in the 2°C isotherm. This may reflect the generally less severe sea-ice conditions to the southeast of the island, or it may be due to the siting of the camp or the height at which temperatures were measured. (For instance, one of the July means from this station had to be dropped, as the station description noted that the screen was located at ground-level.) This emphasizes the care with which field-station data must be handled.

Although the Sverdrup Lowlands and Eureka intermontane areas provide the greatest contrast in sea-level climate within the QEI, several other distinctive regions exist, such as the northeastern corner of Ellesmere Island and the area surrounding the North Water and northern Baffin Bay. They too should be integrated into future regional-scale studies.

Though it is necessary to increase the surface-data coverage, especially inland where accurate long-term climate stations are lacking, and to strive for long-term accurate data, greater use can be made of the existing records. Incorporation of oil-camp data is a first step. The coverage can also be considerably increased by constructing maps of 00Z and 12Z temperature from the morning and evening Polar Shelf field-station data. These can then be compared to the daily mean temperature maps, thus providing valuable information

in some critical areas. Evaluation of the magnitude of the errors associated with the various types of data is also needed.

The details of the temperature-patterns will undoubtedly change with the addition of new stations and more comprehensive techniques for using field-station data; however, this will not alter the S-shape or general features of the present synoptic-scale climate configuration. Strong interannual variations do occur, though, and the pattern may be amplified or reversed seasonally, and may alter with long-term climate change.

Precipitation

Precipitation measurements in the Arctic are subject to serious inaccuracies. Winter snow-accumulation values from the permanent weather stations appear to be underestimated by 40 to 400% (Koerner 1979; Maxwell 1980; Woo *et al.* 1983).

Mean total annual precipitation, mean total summer precipitation and mean snow-depth on 31 January have been plotted (Figure 12a,b). Areas over 600 m or covered by ice caps were ignored, to be consistent with the regional (near sea level) temperature analysis.

Total annual (Figure 12b) and summer precipitation (Figure 12a) and winter snow-depth (Figure 12a) values all show similar distributions. The highest precipitation occurs in the area under the direct influence of the North Water and Baffin Bay cyclone. A secondary maximum is found to windward of the mountain barriers on northern Ellesmere and Axel Heiberg islands. Precipitation minimums occur in the Eureka Sound intermontane region due to the precipitation-shadow effect, and in the far western islands due to the proximity of the persistent surface anticyclone.

Precipitation amounts, thus, do not produce the same S-shaped pattern as seen in the temperature analyses. This indicates that at a regional scale they are controlled by a different mechanism. Previous studies have also suggested that the major control on precipitation is the frequency and intensity of cyclonic activity, and that the interaction of topography and mean atmospheric flow is secondary (Müller *et al.* 1976; Maxwell 1980; Bradley and Eischeid 1985). Considerably more study of the synoptic situations responsible for extreme and significant precipitation events is necessary, not only to determine the regional patterns and their effects, but also to establish source regions for the moisture, pollen and aerosols composing that precipitation.

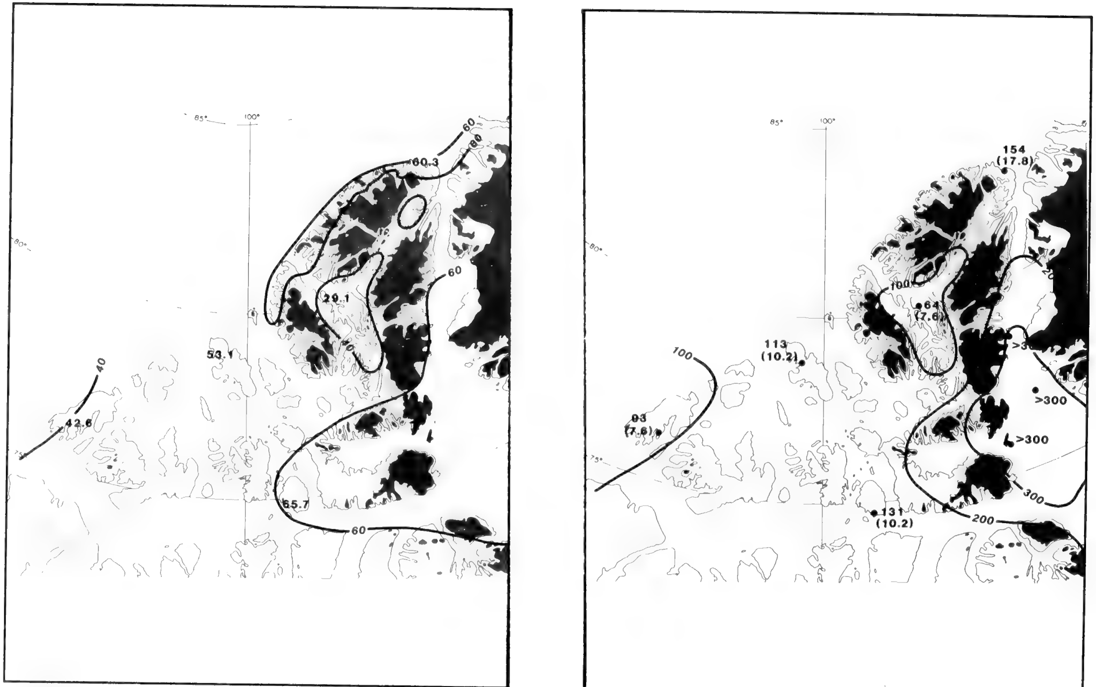

FIGURE 12: (a) Mean total summer (June, July and August) precipitation in mm (contoured) for the Queen Elizabeth Islands; (b) Mean total annual precipitation (mm) and snow-depth at the end of January in cm (in brackets)

SUMMARY

Implications of Regional-Study Results

The prevailing atmospheric flow into the Queen Elizabeth Islands comes from the area of radiation minimum - the area where least heat is available. Air-masses which have their source here have been cooled by the vast expanse of the central Arctic Ocean pack ice. The topography of the QEI modifies the radiation and general circulation-patterns producing several distinctive regions. In the Sverdrup Lowlands, an incoming radiation minimum combines with a cold advection maximum. In the intermontane regions of Axel Heiberg and Ellesmere islands, a radiation maximum combines with a minimum of cold-air advection.

The resulting regional climatic contrasts are reflected in distributions within the biosphere and geosphere. Edlund and Alt (1989) concluded that regional-vegetation patterns respond strongly to these controls. Vegetation in the Eureka Sound intermontane area rivals that on southern Victoria Island, while the Sverdrup Lowlands climate produces Beschel's (1969) "Barren Wedge". The inter-island channels within the Sverdrup Lowland remain ice-covered all summer in contrast to Eureka Sound which is navigable in all but the most severe seasons. Mass-balance regimes of glaciers and ice caps exposed to the central Arctic Ocean are characterized by low summer melt-values and the occurrence of summer accumulation (Alt 1975, 1987). Within the Eureka Sound intermontane area outlet glaciers are subject to considerably more summer melt resulting in elevated equilibrium lines (Hattersley-Smith 1969).

Paleoenvironmental records from the two distinct areas would be expected to indicate differing climatic conditions and responses. The specific nature of the differences would depend on the circulation and surface-conditions prevailing at earlier times. Similarly, the effect of future climate and environmental changes would not necessarily be uniform across the QEI, depending on the specific nature of those changes and their synoptic-scale effects. Future interactive studies of environmental change will need, in addition to a more complete database, detailed analysis of the synoptic situations associated with regional patterns and anomalies.

Gaps

A glance at any surface-weather map showing the observing stations in existence in the Canadian Arctic in general, or in the QEI specifically, will convey clearly the problems of representativeness that need to be overcome. Many of these have also been illustrated by the results of this QEI case study. The problems relate to geographical coverage, surface-conditions, inter- and intra-annual continuity, observational frequency and uniformity in terms of elements observed and instrumentation used.

There are many obvious blanks in geographical coverage. The Viscount Melville Sound area is a large one. In the QEI, since the closing of Isachsen in 1978, the entire Sverdrup Lowlands has no station in the observing network whatsoever, and problems such as the seemingly warm area around King Christian Island cannot be resolved given present data-coverage. The southern Ellesmere-Devon island region is similarly unrepresented, including the Canadian side of the North Water.

As mentioned earlier, the Canadian Arctic Islands present a complex mosaic of differing surface-conditions. Such a region requires a much denser coverage of observing sites to allow a thorough characterization of the climate than would a region with more uniform conditions. Unfortunately, in the Arctic Islands, station density is lower than that of more uniform regions of Canada. This problem is compounded by the almost exclusively coastal location of stations. Inland and offshore areas are only represented by short-term data-programs.

Looking at maps of station sites can be deceptive in several ways beyond the obvious problems of geographical coverage and surface representativeness. For example, a map showing all climate-observing stations active within the QEI since 1972 would suggest an impressively thorough coverage. It would include some 200 Polar Shelf-supported sites, about 60 Panarctic sites, as well six AES network stations. The Polar Shelf stations are the only ones including inland sites (however, they are only operational in summer and in most cases for limited parts of that season). Additionally, many stations have been in existence for only one summer. The Panarctic sites include both onshore and offshore locations, but data from the latter are restricted to winter observations taken at on-ice installations. Like the Polar Shelf stations, Panarctic activities tend not to last more than a year or so at any given site. Only the AES stations offer operational continuity, although Isachsen's record ends in 1978. However, the exclusively coastal siting of AES stations must be considered.

As a result, for evaluating July mean temperature, only the six AES stations offered long-term continuous records. About 30 of the 200 Polar Shelf and 12 of the 60 Panarctic stations (although the latter were not used) provided July values for various individual years; less than a third of these have more than a one-year record. This resulted in considerable station-by-station evaluation and adjustment - highly subjective at times.

The other aspect of data-usefulness not apparent from simple station lists or maps is the frequency with which observations are taken each day. Statistics based on observations taken twice daily can be significantly different from those of hourly observations. Such disparities in frequency are common for the various stations from which data are collected in the Arctic Islands, and they occur not only between networks of stations operated by different agencies, but also within such networks. Improved analytical techniques must be developed to handle such data.

The range of climatic elements observed at any station can also vary considerably. The problem is not so great with the basic elements such as temperature, wind, pressure, visibility, etc., but with the more specialized ones such as radiation, snowcover, soil-temperature and the like. Of course, the generally greater complexity and cost of the necessary instrumentation is a factor. Though the problem is far from being exclusively an arctic one, the remoteness of the area adds substantially to the cost. The difficulties of trying to evaluate areal patterns when coverage is incomplete spatially and incompatible temporally are apparent from the discussion of radiation in this QEI case study.

Ways to overcome these gaps are not simple. We cannot merely set up conventional, manned stations wherever they are needed, because the costs involved are prohibitive. Less expensive data-gathering alternatives must be found. More advantage must also be taken of existing capabilities and developing technologies, and greater use must be made of data already available.

These approaches are now being increasingly recognized and applied. For example, the work of Edlund and Alt (1989) and this paper represent the first broad use of the Polar Shelf climate data-set, although individual station-data have contributed to a number of studies. The results of this case study suggests the greater potential, not only of the Polar Shelf data, but also of other non-AES sources such as the oil industry (Panarctic data from the QEI and the Dome/Gulf Beaufort drilling), the Arctic Buoy Program in the Arctic Basin, ice-island data, and gridded surface and upper-air data-sets available through the

United States. Even the AES network station data are not fully exploited; fields such as cloud, radiation, snowcover, etc. offer useful opportunities. With the data that are already available, then, it is important to recognize the deficiencies. But, having done that, it is essential to examine how such data can be applied directly, or made more useful through appropriate comparisons with other data or through calibrations with physical variables related to sea ice, permafrost and glaciers (for example) which will allow extending or improving existing records.

A method of obtaining new data that has become increasingly feasible in the Arctic Islands with advances in technology is the use of automatic remote climate stations. Such an installation equipped to record air-temperature, shallow soil-temperature, wind-speed and direction, humidity, radiation, and snow-depth and capable of untended year-round operation, costs in the order of $10,000 to $15,000 depending on the particular sensor-configuration. Data are stored in electronic-memory modules that can be accessed as required. It is desirable to visit such installations annually, but as they are usually established in conjunction with programs where climate is only one component, the annual visit can be timed to fit other field activities so that no additional cost is incurred. Examples are the interdisciplinary programs at Hot Weather Creek on Fosheim Peninsula, Ellesmere Island (Edlund *et al.* 1989) and at Amadjuak and Nettilling lakes on Baffin Island (Jacobs *et al.*, this volume). An important concern as such installations become more prevalent is standardization of instrumentation, climate elements observed, and observing frequencies. Uniformity here will facilitate data-comparison and easy application of analysis-programs and systems.

Satellites have the potential to provide, at least on a regional scale, some of the climate and climate-related information that is so difficult and expensive to acquire using conventional methods. An advantage of this approach is the continuous rather than discrete areal sampling that is possible. This is a distinct benefit among the Arctic Islands with its varied surface-characteristics. Useful data can be obtained for such climate and related elements as air-temperature, winds, waves, cloud, snowcover and sea ice. Microwave technology, for example, is beginning to show considerable potential for sea-ice studies, particularly in respect to sea-ice type (age) definition and details of ice-extent. The U.S. Defense Meteorological Satellite Program using the recently launched Special Sensor Microwave Imager (SSM/I) offers the best opportunity yet for routine, daily, all-weather sea-ice coverage in near real

time. A data-processing and management system making the resulting data available to the research community is being developed by several interested U.S. agencies.

Our understanding of the climate of the Canadian Arctic Islands is still, in many ways, incomplete. We have tried to show why that is so, particularly in one specific geographical area of the islands. In so doing, it has been possible to suggest some general measures by which our understanding could be improved. The high level of interest in the Canadian Arctic Islands which continues to be reflected in the extensive field research programs being undertaken each year, as well as the developing global-change issue, provides hope that such measures will be pursued.

ACKNOWLEDGEMENTS

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Illustrated by Brenda Carter

L'EXPOSITION DES PLAQUES DE NEIGE RÉSIDUELLES DANS L'ARCTIQUE CANADIEN

Lagarec, Daniel[1], Bernard Lauriol[1], et Daniel Devocht[1]

Résumé: Dans l'arctique canadien, la neige subsiste durant tout ou une partie de l'été sous trois formes: les glaciers, les champs de neige et les plaques de neige. Les deux premiers types sont principalement concentrés sur la façade orientale des îles de Baffin, Devon et Ellesmere. Par opposition, les plaques, elles, se rencontrent sur à peu près toutes les îles, bien qu'elles soient plus nombreuses dans la région du détroit d'Hudson que sur les îles de l'ouest de l'arctique.

L'objectif de cet article est de montrer que l'exposition des plaques de neige à travers l'arctique canadien pour l'été de 1958 pour lequel plusieurs couvertures aériennes sont disponibles est expliquée par la direction des vents de l'hiver précédent.

L'épaisseur maximale de neige au sol est la plus forte dans la péninsule de l'Ungava avec 195 cm et décroît jusqu'à 18-25 cm dans le nord-ouest. Elle est atteinte habituellement entre le 1er mars et le 1er mai. Dans la plupart des stations, la neige a disparu le 1er juillet.

On observe un patron assez clair d'exposition des plaques de neige: (1) dans l'ouest, la direction dominante est E à SE; (2) dans l'est, elle est essentiellement SW à NW; (3) dans la partie centrale, comme sur la péninsule de Boothia, il est moins bien défini avec toutefois une dominante SSE.

Dans l'ensemble, ce patron est conforme à la direction des vents dominants de l'hiver, les plaques de neige subsistant sur le côté sous le vent. Dans quelques cas exceptionnels, l'exposition des plaques de neige est déterminée par la direction du vent pendant les mois à fortes chutes de neige.

Abstract: In the Canadian Arctic, snow remains on the ground in summer as glaciers, snowfields or snowbanks. The first two types are mainly located on the eastern margins of Baffin, Devon and Ellesmere islands. In contrast, snowbanks may be found on almost every island, although they are more numerous around Hudson Strait than on the western islands of the archipelago.

The aim of this paper is to show that the orientation of snowbanks across the Canadian Arctic for the summer of 1958, for which several aerial-photograph coverages are available, is explained by the direction of the previous winter winds.

Maximum snow-depth of 195 cm was observed in the Ungava Peninsula and decreased to a minimum of 18-25 cm in the northwest. The maximum depth is usually achieved between March 1 and May 1. At most stations, snow has melted by July 1.

A clear pattern of orientation of snowbanks appears: (1) in the western region, the dominant direction is E to SE; (2) in the East, it is mainly SW to NW; (3) in central locations, for example on Boothia Peninsula, it is less defined, with however a SSE dominance.

Overall this pattern is consistent with winter prevailing winds, the snowbanks resting on the leeside of raised features. In exceptional cases, snowbank orientation is related to the wind direction of months with heavy snowfalls.

INTRODUCTION

Dans l'Arctique canadien, la neige subsiste durant tout ou une partie de l'été dans trois types de situations: les glaciers, les champs de neige et les plaques de neige. Les deux premiers sont principalement concentrés sur la façade orientale des îles de Baffin, Devon et Ellesmere. Les plaques, elles, se rencontrent sur à peu près toutes les îles, bien qu'elles soient plus nombreuses dans la région du détroit d'Hudson que sur les îles de l'Ouest de l'Arctique (Lauriol *et al.* 1984, 1986).

Les raisons de la distribution inégale des surfaces enneigées en été résident essentiellement dans des différences climatiques; il semble notamment qu'il y ait une relation

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entre l'épaisseur de la neige au sol à la fin de l'hiver et la superficie occupée par la neige à la fin du mois de juillet. Cette relation paraît assez forte pour qu'on puisse envisager la possibilité d'utiliser la surface résiduelle de la neige comme moyen de connaître l'épaisseur de la neige au sol à la fin de l'hiver (Lauriol *et al.* 1986).

Dans le présent article, nous voulons montrer et expliquer les caractéristiques de l'exposition des plaques de neige à travers les îles de l'Arctique canadien pour l'été 1958.

MÉTHODOLOGIE ET OBJECTIFS

Les objectifs de l'étude sont d'identifier des zones où l'exposition des plaques de neige est homogène et d'évaluer la relation entre celle-ci et l'orientation des vents à une station météorologique proche. L'exposition des plaques de neige a été déterminée à partir de photographies aériennes de la Photothèque Nationale et les données sur les vents ont été extraites des sommaires climatiques mensuels d'Environnement Canada. Il est à noter que nous avons conservé la toponymie en vigueur à cette époque.

Bien qu'en règle générale, d'une année à l'autre, les plaques de neige se retrouvent aux même endroits, il a paru utile pour faciliter les comparaisons de n'utiliser que des photographies prises au cours de l'été 1958. Le choix de cette année s'explique par la couverture extensive existant pour cette année-là.

Le problème le plus difficile à surmonter fut de trouver des zones où les accidents topographiques à l'abri desquels la neige était susceptible de s'accumuler, n'offraient aucune orientation dominante ou contraignante. Celles qui se prêtaient le mieux à l'analyse étaient les plateaux sur lesquels se rencontraient quelques accidents topographiques, en relief ou en creux, offrant des possibilités d'exposition variées.

RÉSULTATS

L'exposition des plaques de neige a été mesurée selon un système de huit points cardinaux. Toutefois pour simplifier la représentation et permettre des comparaisons, nous avons calculé pour chaque site la direction moyenne ainsi que le vecteur résultant qui se

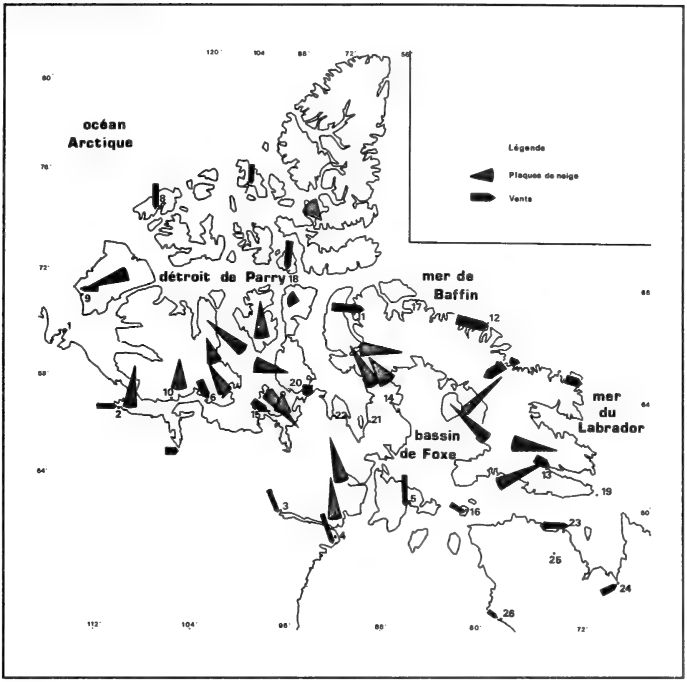

FIGURE 1: Orientation dominante des plaques de neige et des vents au cours de l'hiver 1957-1958.

trouve à exprimer l'intensité du groupement autour de la direction moyenne. De sorte que sur la figure 1, la longueur du symbole utilisé reflète le vecteur résultant et la largeur l'erreur-type au seuil de 95 % (Davis 1986).

Les coordonnées de l'extrémité de chaque vecteur dont la direction est représentée par l'angle θ sont:

$$X_i = \cos \theta_i$$
$$Y_i = \sin \theta_i$$

Le vecteur résultant est obtenu en sommant les sinus et cosinus de chaque vecteur. La direction moyenne est alors déterminée par:

$$[1] \qquad \bar{\theta} = \tan^{-1} \left(\sum_{i=1}^{n} \sin \theta_i \Big/ \sum_{i=1}^{n} \cos \theta_i \right)$$

et longueur du vecteur résultant R est donnée par le théorème de Pythagore:

$$[2] \qquad R = \sqrt{\left(\sum_{i=1}^{n} \cos \theta_i \right)^2 + \left(\sum_{i=1}^{n} \sin \theta_i \right)^2}$$

et dépend de la taille de la population considérée. Pour permettre les comparaisons, on peut standardiser en calculant la longueur moyenne $\bar{R}$ en divisant la longueur du vecteur résultant par le nombre de cas. Ce nouveau paramètre a une valeur comprise entre 0 et 1 et représente une mesure de dispersion analogue à la variance, mais exprimée en sens inverse: des valeurs élevées indiquent que les observations sont bien groupées autour de la moyenne, alors que des valeurs faibles indiquent une forte dispersion. Il serait plus juste de parler d'indice de concentration.

Sur la figure 1 montrant les informations ainsi schématisées pour chaque site, on peut distinguer trois grandes régions:

(1) À l'Ouest, sur les îles Banks et Victoria, l'orientation dominante est d'Est à Sud-est et l'indice de concentration est supérieur à 0.5, atteignant un maximum de 0.815 dans le Nord de Victoria;

(2) À l'Est, en bordure de la mer de Baffin (îles de Baffin, Somerset et Devon), la dominance se situe dans le secteur Sud-ouest à Nord-ouest et la dispersion augmente vers le Nord-ouest alors que l'indice de concentration passe d'un maximum absolu de 0.926 dans le centre de l'Île de Baffin à un minimum absolu de 0.169 sur l'Isle de Somerset;

(3) Entre les deux, on retrouve une zone plus hétérogène avec néanmoins une dominance d'orientation Sud sud-est et une diminution de la dispersion vers le sud, dans le district de Keewatin, où l'indice atteint 0.7.

Afin de tenter d'expliquer ce patron, il est important de bien connaître les conditions climatiques d'ensemble de l'hiver responsables de la disponibilité en neige ainsi que des vents influençant sa mise en place. Il est à noter que nous avons conservé la toponymie en usage à l'époque et que les numéros de la figure 1 correspondent aux stations apparaissant dans le tableau 1.

TABLEAU 1: *CHUTES DE NEIGE AU COURS DE L'HIVER 1957-1958 DANS L'ARCTIQUE CANADIEN (EN CM).*

		AOÛT	SEPT	OCT	NOV	DÉC	JAN	FÉV	MARS	AVR	MAI	JUIN	TOTAL[1]	NORMALE[1]
1	Cape Parry	0	17.8	5.1	0.5	0.8	T	T	-	3.6	0.2	T	(35.0)	125.9
2	Coppermine	0	8.1	8.1	15.7	1.0	9.1	1.3	7.6	12.2	1.5	1.5	66.8	100.7
3	Baker Lake	0	7.9	10.4	6.6	2.0	8.6	0.2	6.6	5.8	3.8	1.5	53.6	100.0
4	Chesterfield	0	T	5.3	12.4	3.8	10.2	7.6	5.6	3.8	6.1	3.8	58.7	112.5
5	Coral Harbour	0	12.4	13.7	17.3	7.1	21.3	9.4	8.9	12.4	23.4	7.1	133.0	131.9
6	Cambridge Bay	T	8.4	12.7	18.0	4.8	13.0	4.1	10.9	5.1	5.6	3.8	86.4	76.8
7	Isachsen	11.4	2.5	6.6	T	T	1.3	3.3	0	0.5	7.6	0.3	33.5	81.3
8	Mould Bay	8.1	6.1	5.1	2.0	2.3	11.7	2.0	2.3	1.0	4.1	T	44.7	71.9
9	Sachs Harbour	T	5.1	7.9	2.8	0.8	2.3	1.3	1.0	2.0	1.3	0.3	39.9	76.0
10	Unnamed Point	0	7.1	29.0	T	1.3	2.8	2.5	0	3.6	3.0	3.6	52.8	45.8
11	Arctic Bay	T	10.7	13.2	1.3	0.8	6.6	4.8	1.8	0.8	0.3	1.5	41.7	71.5
12	Clyde	T	4.3	41.7	13.5	1.3	4.6	5.3	2.8	1.8	7.4	3.0	85.6	168.9
13	Frobisher Bay	4.3	1.3	53.8	62.7	63.5	76.5	45.5	66.3	73.9	30.0	12.4	490.2	255.5
14	Hall Lake	3.3	1.5	16.5	8.4	3.0	5.1	14.5	4.1	8.4	28.4	7.1	100.3	121.3
15	King William	0	7.6	-	8.1	2.5	23.4	3.6	31.4	1.0	7.9	-	(85.0)	51.2
16	Nottingham I.	T	21.1	27.7	33.0	32.3	33.3	11.2	8.6	32.0	16.5	29.7	245.4	149.8
17	Pond Inlet	0	0.6	2.0	T	T	0.8	1.6	0.6	T	5.1	-	(10.4)	(110.0)
18	Resolute	0.3	16.3	19.8	3.3	3.3	2.5	4.3	3.8	3.0	5.8	4.3	66.8	83.8
19	Resolution I.	T	3.8	21.1	20.1	30.7	12.2	12.2	7.4	6.4	24.1	-	(150.0)	155.4
20	Spence Bay	0	11.7	10.4	2.0	T	3.3	13.5	1.0	4.3	10.7	12.4	69.3	103.3
21	West Melville	-	-	-	12.2	0.8	1.8	20.6	1.5	16.8	28.4	2.3	(100.0)	97.0
22	West Simpson	0	26.9	19.3	42.2	0.5	10.7	5.6	7.6	36.3	10.7	6.4	165.6	127.1
23	Cape Hope	3.8	8.9	36.6	64.3	81.0	42.2	25.4	22.1	19.8	16.5	5.1	325.6	147.3
24	Fort Chimo	T	0.3	9.4	23.4	61.5	43.9	30.2	16.8	17.5	51.8	12.4	267.2	236.7
25	Payne River	-	0.5	14.7	82.6	76.2	-	-	-	-	32.5	8.9	-	-
26	Port Harrison	T	T	10.9	25.9	16.5	2.0	7.1	2.3	9.4	22.4	1.5	98.0	122.9

[1] Les valeurs entre parenthèses sont des estimations.

LES CONDITIONS CLIMATIQUES DE L'HIVER 1957-1958

Les caractères généraux de la circulation atmosphérique

Dans l'ensemble, la circulation en altitude (700 mb) se caractérise par une crête sur le Yukon et une vallée sur l'Est du pays. Ce patron est assez constant au cours de l'hiver, sauf en mars dont le cas sera discuté plus loin. Toutefois, son intensité varie et contribue à expliquer le régime des précipitations ainsi que l'asymétrie Est-Ouest de ces dernières: la crête sur le Yukon permet la pénétration limitée d'air humide sur la façade occidentale de l'archipel où le maximum des chutes de neige se produit en septembre-octobre, alors que la vallée orientale favorise la remontée d'air atlantique le long de la façade orientale; le déplacement vers le Nord du creux au cours de l'hiver se traduit par un décalage de la date du maximum des précipitations nivales qui arrive en novembre-décembre au sud du détroit d'Hudson et en janvier au Nord. En mars, une haute pression occupe la mer d'Hudson ce qui provoque une dominance du flux d'Ouest et de faibles chutes de neige, sauf sur la façade atlantique.

En surface, le champ de pression moyen résultant de cette circulation montre deux centres de haute pression, l'un centré sur le Keewatin et l'autre au Nord-ouest, et un centre de basse pression localisé sur la mer de Baffin. Barry (1960) a montré que le Nord de l'Ungava a connu au cours de l'hiver 1957-1958 une forte dominance de flux cycloniques du Nord-ouest, modifiés ou non (40 %), et d'Ouest (25 %).

Distribution des chutes de neige et de la neige au sol

La carte du total des chutes de neige (figure 2) montre une forte asymétrie de la distribution opposant le Sud-est et le Nord-ouest. Les maxima sont observés à Frobisher Bay (Iqaluit) (490 cm) et Cap Hopes Advance (326 cm). Deux zones de minima apparaissent dans le Nord de l'île de Baffin (10 cm à Pond Inlet) et sur la façade de l'Océan Arctique (33 cm à Isachsen). Si l'on compare avec les normales, on remarque que 15 stations sur les 26 utilisées ont des totaux inférieurs à celles-ci. Les 11 autres sont localisées le long d'un axe Cambridge Bay-Détroit d'Hudson.

Dans l'ensemble, octobre-novembre et mai sont les deux périodes recevant les plus grandes quantités, mais les régimes varient spatialement. Les stations du Nord-ouest ont

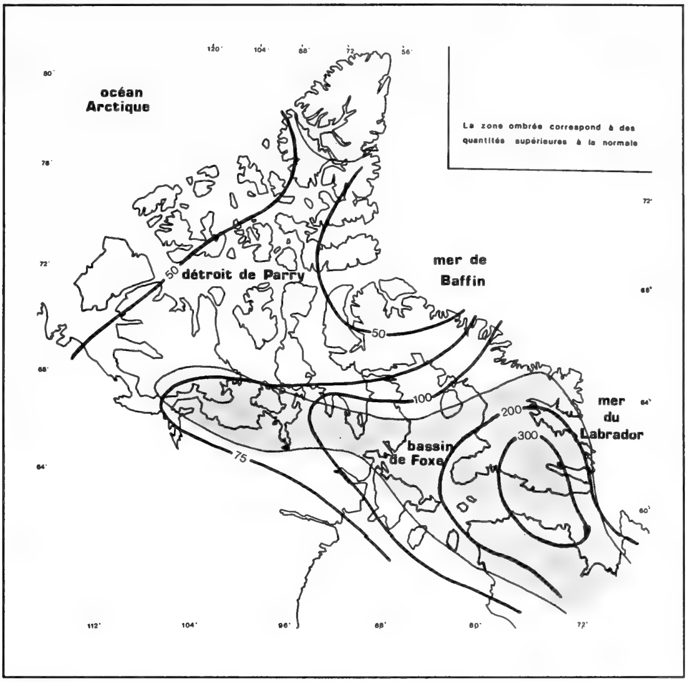

FIGURE 2: Chutes de neige de l'hiver 1957-1958 (en cm).

leur maximum au début de l'hiver, et même en août dans le cas d'Isachsen; celles d'Ungava au coeur de l'hiver et celles de la partie centrale (Keewatin oriental) en mai. Frobisher Bay (Iqaluit) constitue une exception, les chutes étant abondantes pratiquement d'octobre à mai.

L'épaisseur maximale de neige au sol est la plus forte autour du détroit d'Hudson avec un maximum de 195 cm dans l'Ungava, et décroît selon un gradient Sud-est-Nord-est, pour n'être plus que de 18 à 25 cm le long du littoral arctique. Elle est atteinte le plus souvent le 1er mai, à l'exception de l'Ungava, du nord de l'île de Baffin et des îles du Nord-ouest où cela se produit le 1er avril ou même le 1er mars. Ce patron reflète assez bien celui des chutes de neige. Quelques différences sont à noter par rapport aux normales. Ainsi les valeurs sont plus fortes dans l'axe Cambridge Bay-Détroit d'Hudson. Mais surtout, il semble que les dates du maximum sont dans l'ensemble plus tardives d'environ un mois.

Pour la plupart des stations, la neige a disparu le 1^{er} juillet. La fusion est le plus souvent un phénomène catastrophique, comme à West Simpson où l'on passe de 104 cm le 1^{er} juin à 2.5 cm le 1^{er} juillet (Tableau 2). Dans l'est, l'essentiel de la fonte a lieu en mai. Selon les normales, la neige a généralement disparu le 1^{er} juillet à l'exception de quelques îlots sur Baffin qui peuvent durer jusqu'au 15 juillet (Maxwell 1980).

TABLEAU 2: *HAUTEUR DE NEIGE AU SOL, 1957-1958 (EN CM).*

		SEPT	OCT	NOV	DÉC	JAN	FÉV	MARS	AVR	MAI	JUIN
1	Cape Parry	12.7	15.2	15.2	15.2	18.0	18.0	18.0	18.0	18.0	0
2	Coppermine	5.1	7.6	18.0	20.3	27.9	27.9	35.6	43.2	10.2	0
3	Baker Lake	T	5.1	7.6	15.2	20.3	20.3	22.9	25.4	20.3	2.5
4	Chesterfield	0	2.5	18.0	22.9	35.6	45.7	48.3	45.7	33.0	2.5
5	Coral Harbour	T	7.6	18.0	20.3	35.6	38.1	40.6	45.7	33.0	T
6	Cambridge Bay	2.5	20.3	35.6	38.1	45.7	48.3	55.9	58.4	45.7	0
7	Isachsen	2.5	12.7	12.7	12.7	12.7	15.2	15.2	15.2	18.0	T
8	Mould Bay	2.5	7.6	10.2	10.2	22.9	22.9	25.4	25.4	25.4	T
9	Sachs Harbour	7.6	12.7	18.0	18.0	20.3	20.3	22.9	22.9	25.4	T
10	Unnamed Point	2.5	15.2	18.0	20.3	25.4	25.4	27.9	18.0	7.6	0
11	Arctic Bay	0	7.6	12.7	15.2	20.3	27.9	30.5	30.5	27.9	2.5
12	Clyde	T	40.6	53.3	55.9	61.0	66.0	68.5	68.5	61.0	5.1
13	Frobisher Bay	0	10.2	20.3	38.1	30.5	45.7	61.0	86.4	12.7	0
14	Hall Lake	T	10.2	18.0	20.3	25.4	35.6	35.6	43.2	30.5	T
15	King William	7.6	-	45.7	48.3	71.1	78.7	91.4	55.9	10.2	-
16	Nottingham I.	T	7.6	38.1	71.1	104.1	114.3	104.1	127.0	30.5	T
18	Resolute	12.7	18.0	22.9	20.3	18.0	20.3	20.3	20.3	20.3	0
19	Resolution I.	T	12.7	38.1	68.5	78.7	86.4	88.9	38.1	27.9	-
20	Spence Bay	7.6	12.7	12.7	12.7	15.2	20.3	20.3	22.9	20.3	T
21	West Melville	-	-	40.6	40.6	30.5	43.2	38.1	48.3	35.6	0
22	West Simpson	20.3	38.1	50.8	50.8	61.0	63.5	71.1	106.7	104.1	2.5
23	Cape Hope	0	18.0	63.5	94.0	78.7	94.0	96.5	91.4	43.2	10.2
24	Fort Chimo	0	5.1	10.2	48.3	58.4	71.1	33.0	20.3	10.2	0
25	Payne River	0	7.6	71.1	137.2	177.8	188.0	177.8	195.6	152.4	-
26	Port Harrison	0	5.1	27.9	45.7	48.3	55.9	48.3	30.5	5.1	T

Pour des chutes de neige inférieures à 100 cm, la relation hauteur de neige au sol/précipitations est relativement bonne et linéaire:

[3] $H_{max} = 1.08P - 15$ cm ($r=0.846$; significatif à 0.001).

Quand les précipitations sont supérieures à ce seuil, aucune relation n'apparaît clairement.

Les vents

L'orientation des vents a été appréhendée de la même façon que celle des bancs de neige, c'est-à-dire que pour chaque station, on a déterminé l'orientation moyenne, l'erreur-type au niveau 0.05 et le vecteur moyen. Ces données apparaîssent sur la figure 1. Lors du calcul de ces paramètres, nous n'avons pas tenu compte des calmes. Il convient de noter que ceux-ci présentent une organisation spatiale très nette selon un gradient Nord-est-Sud-ouest, avec un maximum supérieur à 40 % dans le nord de l'Île de Baffin et une décroissance vers le Sud-ouest où les valeurs sont inférieures à 10 %.

L'orientation moyenne des vents présentée sur la figure 1 correspond assez bien à celle déduite du champ de pression moyen pour la période. D'une dominante Nord-Nord-ouest au sortir du centre de haute pression localisé dans la partie occidentale de l'archipel ou Ouest quand ils viennent de celui du Keewatin, la direction des vents s'infléchit progressivement à Nord-ouest dans la partie centrale jusqu'à devenir franchement d'Ouest en Ungava.

L'indice de concentration montre un patron en ensellement avec des valeurs supérieures à 0.5 dans la partie centrale diminuant de part et d'autre. La relative stabilité des orientations dans la partie centrale s'explique par le caractère transitionel de cette région, alors que dans les deux autres, les centres de hautes et basses pressions se déplacent légèrement au cours de l'hiver.

CONCLUSION

L'examen de l'orientation des plaques de neige et des vents dominants montre qu'il existe dans l'ensemble une assez bonne concordance entre les deux et que la neige se dépose du côté sous le vent. Toutefois quelques disparités apparaissent sur la figure 1. Si l'on regarde ces cas déviants de plus près, on constate que généralement les plaques de neige s'organisent non pas par rapport au vent moyen de l'hiver, mais par rapport à un vent dominant ou sous-dominant d'un mois où les chutes de neige ont été relativement importantes. Le secteur de Baffin constitue un des cas déviants les plus typiques avec des dominantes d'orientation vers un secteur Sud-ouest-Nord-ouest. Or, au début de l'hiver quand se produisent des chutes de neige assez abondantes, les vents dominants ou sous-

dominants viennent du secteur Nord-est à Sud-est et c'est aussi l'époque où ils sont les plus forts (6.3 m/s).

Dans le cas de l'île de Banks, l'orientation dominante des bancs de neige est vers l'Est et les vents dominants viennent de l'Est. Mais en octobre quand tombe une bonne partie des précipitations neigeuses, les vents dominants viennent de l'Ouest et c'est aussi le mois où ils sont les plus forts (7.3 m/s).

L'examen des cas déviants permet d'avancer que la formation des plaques de neige est sans doute précoce et se produit au début de la saison nivale par l'apparition de noyaux autour desquels elles vont se développer. Les vents forts relevés pour cette époque contribuent en effet à augmenter la densité de la neige accumulée (Föhn 1980).

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ARCTIC METEOROLOGY AND CLIMATOLOGY, PRESENT STATE AND FUTURE DIRECTIONS

Claude L. Labine[1]

Abstract: A review of the problems of meteorology and climatology of the Canadian Arctic Islands is presented. Problems with the existing database are dealt with first: low density of stations; coastal nature of data; few long-term studies. Further, radiation and surface energy-balance data indicate that there are some basic problems remaining. Permafrost research in the Arctic Islands needs to be more closely linked to surface energy exchanges and climatic change. The largest polynya in the region, the North Water, still needs to be properly understood.

Some positive steps have occurred in the past few years; the air-quality monitoring program at Alert, and the Atmospheric Environment Service climate-permafrost program are two examples. A lack of a clear government northern policy is considered to be the main drawback affecting all research in the Arctic Islands.

Résumé: Les problèmes de météorologie et climatologie des îles de l'arctique sont présentés. Les problèmes de la présente base de données sont discutés en premier: basse densité de stations, influence côtière de l'information, très peu d'études à long terme. L'information du bilan de radiation et d'énergie de la surface démontre encore des problèmes de base. L'étude du pergélisol dans les îles de l'arctique a besoin d'être plus lié aux flux d'énergie de la surface et au changement de climat. La plus grande polynya des îles, l'Eau du Nord, a besoin d'être mieux comprise.

Il y a eu plusieurs directions positives durant les dernières années; l'établissement d'une de station de surveillance de qualité d'air à Alert et l'initiation d'un programme de recherche du pergélisol et le changement de climat sont deux examples. Un manque d'une politique nordique clair et ferme de la part du gouvernement fédéral, est un des grands désavantages qui affectent toute recherche dans les îles de l'arctique.

INTRODUCTION

In preparing papers for this volume, we were asked to establish the highlights of the subject, detect significant gaps in our present understanding, suggest ways of filling such gaps and list basic references. These goals were pursued, as well as two others. The first is from Hattersley-Smith (1982) who reviewed the last Arctic Islands conference held in 1980 in Yellowknife (Zaslow 1981). Unfortunately, that conference did not seem to contribute much forward direction but looked back on past accomplishments. As Hattersley-Smith states: The scientific research papers provide useful summaries of past field work and of knowledge acquired, but some fall short in identifying the main problems to be resolved and in charting the course of future work". Because there has been no similar conference since then, it is imperative that we attempt to focus on the present status of our various disciplines and suggest possible directions.

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The final guidelines used in writing this paper is from Hare (1968), who stated that: "The climatological view of the Arctic absolutely demands the interdisciplinary approach". This is probably true of most arctic scientific disciplines and also implies that some of the points raised in this paper can be applied to other research fields. The interdisciplinary nature of the problem also implies non-scientific influences upon arctic research such as economics, northern government policy, land-claims and arctic sovereignty. Researchers cannot avoid being influenced by these elements. In trying to review and synthesize a discipline, at least the implications of these non-scientific influences should be considered, in order to see how such issues can be best incorporated in the continuing advancement of knowledge about the Arctic Islands - Canada's most unique geographical feature.

PRESENT PROBLEMS

Research Activity

The task of analyzing the present situation and potential direction of arctic meteorology and climatology is not as difficult as it might seem at first. Three important publications in recent years have made the task much easier by presenting extensive overviews of past research (Maxwell 1981; Ohmura 1982A) and, more importantly, by indicating some of the problems in arctic meteorology and climatology (Maxwell 1980). These publications are the best basic references now available. Maxwell's (1980) work is the best source of synthesized climatic data available, and will probably remain a major reference for years to come. Ohmura's (1982A) study offers an excellent historical perspective, not only on energy-budgets but on both meteorology and climatology. My task is therefore reduced to reviewing the past six years of activity, before considering continuing problems and potential directions. This requirement is readily met since the last five years has been a period of the least amount of research activity for meteorology and climatology in the Arctic Islands since the 1951-1955 period following the establishment of the Joint American Canadian Weather Stations in the late 1940s (Figure 1).

The main characteristics of Figure 1 are: (1) the increase of activity since the establishment of the main synoptic weather stations; (2) the peak of activity in the late 1970s; followed by (3) reduction to present levels. Similar data on oceanography in the

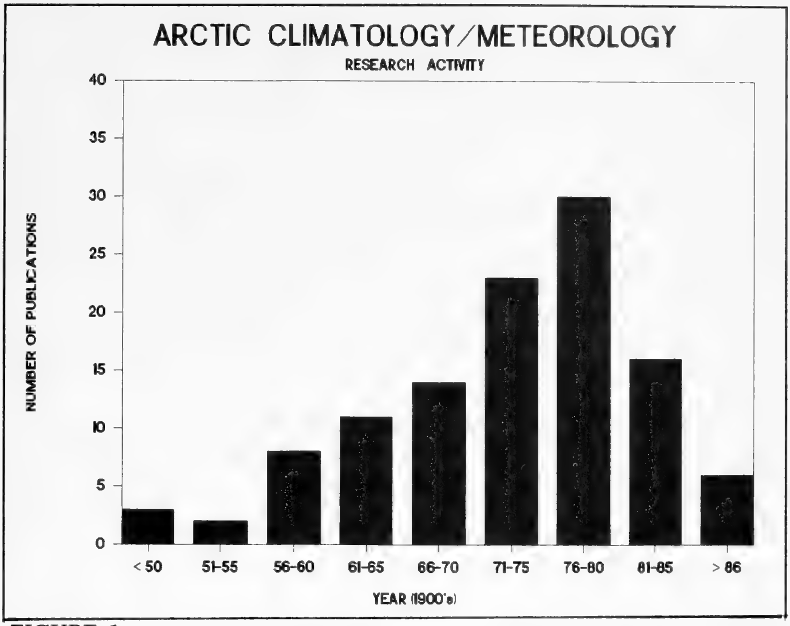

FIGURE 1: Research activity in meteorology and climatology in the Canadian Arctic Islands from 1950 to 1987. Research activity is here defined as the number of research papers published.
Sources: Maxwell 1980, 1981; Ohmura 1982A; Arctic Scientific and Technological Information Services of the Arctic Institute of North America (ASTIS).
Key words used in the search: meteorology, climatology, hydrology, glaciology, oceanography, water-quality.

Canadian Arctic Islands were discussed by Smiley (1987). Both sets of information show how the search for oil in the Canadian Arctic during the early and mid-1970s coincided with an increase in research activity. In many situations the increase in research activity was as a result of the increase in oil exploration.

Since then, there have been few research projects where the emphasis was on meteorology or climatology. Hydrometeorlogical work by Woo and Marsh (Marsh and Woo 1981; Woo *et al.* 1983) at Resolute was a major contribution to our understanding of the precipitation regime of the Arctic Islands. Research by Bradley and others (Bradley and Serreze 1987; Serreze and Bradley 1987) on a small ice cap was an attempt to understand the processes related to ice sheet-growth and climatic change. Another important meteorological research activity is the work being conducted on "Arctic Haze" by the Atmospheric Environment Service (Barrie and Hoff 1985; Barrie *et al.* 1981). Alt's (1987)

work represents one of the longest sustained efforts of meteorological research in the islands, and is an important contribution to the synoptic climatology of the area. And the glaciological-paleoclimatological research pursued by Koerner (Koerner 1985; Koerner and Fisher 1985) is essential to our understanding of climatic change.

Further proof of the lack of activity in the islands comes from simply reviewing meteorological or climatological projects supported by the Polar Continental Shelf Project. In the last five years there have only been a few active research projects there: Alt's and Koerner's studies, as well as my work (Labine 1988) involving High Arctic oases. Other research projects, where meteorological or climatological aspects were secondary,include a study on a polar semidesert by Addison and Bliss (1980). Unfortunately, these projects were short-term.

This brings us to an apparent problem with arctic meteorology and climatology. In Canada, there is only one university-based research group active in these disciplines. Fortunately, a group once based at McGill University (Hare 1968; Vowinckel and Orvig 1963) has been reconstituted recently as the McGill University Climate Research Group (Harington 1989). There have been some recent visits to the McGill station at Axel Heiberg Island (personal communication, P. Adams), but there are no present plans to pursue long-term climatological or meteorological research from that base. A recent publication, however, dealt with glaciology and some elements of climatic change in that vicinity (Blatter 1987). Last year, Jacobs (Jacobs *et al.*, this volume), from the University of Windsor, initiated a multidisciplinary project on Baffin Island within the context of climatic change. One could argue that research need not be based at a university. Indeed, the majority of present activity is almost exclusively within the federal government - specifically the Arctic Meteorology Section of the Canadian Climate Centre. The central long-term research project undertaken by this group is also involved with climatic change and permafrost. A problem arising from the scarcity of strong university-based groups is that we are not training enough students to deal with the problems of meteorology and climatology in the Arctic Islands.

The Existing Database

As will be shown, there is already an increase in the number of projects directly or indirectly involved with meteorological and climatological research in the Arctic Islands. Although this is promising, it neither removes nor diminishes the impact of existing problems. Simultaneously, this increase in activity will create other problems which need to be addressed. Maxwell (1980, 1981) best summarizes the problems associated with the existing climatic database. The low density of stations is the most obvious characteristic of the synoptic network. With the closing of Isachsen in 1978, only four of the original weather stations are left in the Queen Elizabeth Islands: Alert, Eureka, Resolute and Mould Bay. Although the closing of Isachsen could be justified economically, why was no automatic station established there to at least maintain the database? The existing one was obtained at great expense; the cost of continuing to record the basic parameters would have been insignificant compared to the yearly operating costs of the High Arctic Weather Stations.

Maxwell (1981) also points out that all of these stations are situated on the coasts and certainly bias the database. The strongest gradients occur near the coast (Green 1977) and this database would certainly not show the greater extremes of continentality occurring inland. For example, the difference between a coastal station and one situated 1 km inland on the Alexandra Fiord lowland is clear (Figure 2).

Finally, Ohmura (1982B) states that "In terms of field experimentation, there is no single project which has been continued long enough to be climatologically reliable, and no theoretical or empirical computation scheme of satisfactory accuracy has been developed." Maxwell (1981) also states that "... long term inland and offshore observational programs are relatively few". Obviously, there is a need for long-term research away from the established, staffed stations. It is almost impossible to obtain guaranteed funding for many years, given the nature of our government budgetary system. However, a recent project shows that relatively long-term funding can take place even during a change of government. This was the Northern Oil and Gas Project (NOGAP), which had a seven-year life span. Given the growing interest in climatic change, there needs to be some type of long-term project to determine how the climate is varying. The Arctic Islands are in a unique situation to be the first area to show significant climate change (Bentley 1984).

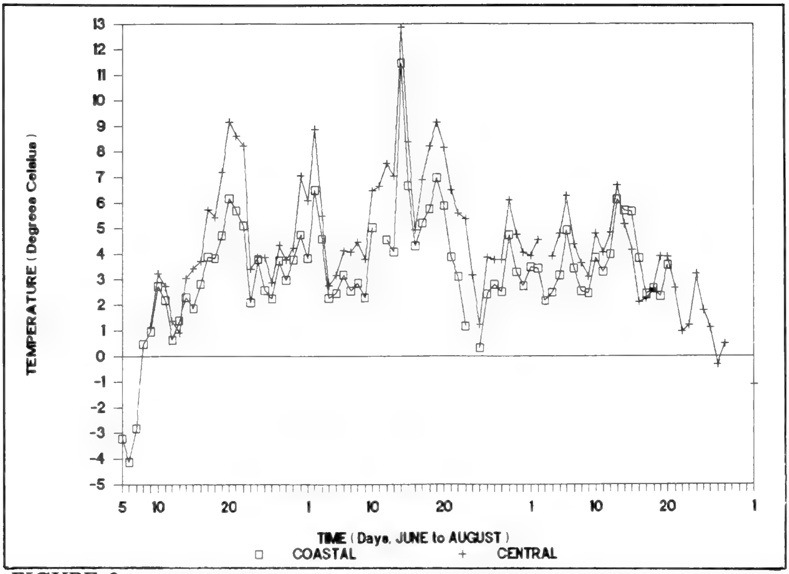

FIGURE 2: 1.5 m air temperature at a coastal station and a central station at Alexandra Fiord, Ellesmere Island. The central station is located approximately 1 km inland from the coast. Note the markedly higher inland temperatures.

Radiation and Surface Energy-Balance

After completing our studies on the oasis area at Truelove Lowland, Devon Island, we (Courtin and Labine 1977) concluded that one of the main reasons that these areas existed was the increased amount of absorbed (net) radiation available to the ecosystem. At the time of the project, in the early 1970s, the Atmospheric Environment Service was just starting radiation measurements in the High Arctic, and we compared our data to the modeled radiation data for Resolute, the closest station. There are now 15 years of data and we find that although the measured values for Resolute are still half of the radiation measured at Truelove Lowland, the net radiation-values for Eureka, Isachsen and Mould Bay are as high as our values for Truelove Lowland. Maxwell (1981) in discussing these data, offers no explanation for this unusual pattern.

Another radiation-related problem stems from Ohmura's statement: The surfaces of the tundra, Arctic Ocean, and the ablation area of polar glaciers were found to receive

similar net radiation during the snow free period despite considerable albedo differences among them". Recent data (Bradley and Serreze 1987) show that there *are* differences in the net radiation values of these surfaces. This indicates that the radiation and energy-balance of surfaces in the Arctic need to be clarified. Radiation and energy-balance characteristics of a surface are at the heart of many other climatic and meteorological factors, and significantly affect permafrost and other parts of the ecosystem.

Polynyas

Heat exchanges occurring over open water were briefly studied at a polynya near Dundas Island (Topham *et al.* 1983). Despite the project's brevity, the results revealed facts about the influence on local ocean currents. Although useful, the data from this small polynya has limited application to the largest polynya in the Canadian Arctic Islands, the North Water, situated in northern Baffin Bay. This large ice-free area was the subject of an intensive study known as the North Water Project in the mid-1970s. Unfortunately, with the death of its director, Dr. F. Müller, a complete, detailed report was never produced. The data are at the Swiss Federal Institute in Zurich. Although perhaps impossible at present, consideration should be given to funding completion of the analysis.

Permafrost

Important, albeit largely descriptive, permafrost research in the Arctic Islands was undertaken by Brown (1972, 1977). Unfortunately, his death left a major gap in this endeavour, and his position at the National Research Council was never replaced. The main permafrost research in the Arctic Islands is now being carried out through Energy, Mines and Resources Canada. This research involves either monitoring temperatures in deep wells (Taylor *et al.* 1983) or permafrost in ocean sediments (Taylor and Allen 1985). Since permafrost is a good integrator of different climatic variables, it is also a good indicator of climatic change. The Arctic Meteorology Section of the Canadian Climate Centre has initiated a climate permafrost program (personal communication, B. Maxwell). Although most of the initial work is in the Low Arctic (Norman Wells, N.W.T.; Churchill, Manitoba; and Schefferville, Quebec), there is a potential for expanding the work to the Arctic Islands. The main information gap involves the influence of climate on permafrost, and requires a better understanding of the surface energy budget in relation to the permafrost layer. Some

research of this kind was initiated by Smith (1975) on the Fosheim Peninsula, Ellesmere Island, but was of short duration.

Summary of Problems

Specifically, the outstanding problems in meteorology and climatology in the Canadian Arctic Islands are as follows:

(1) Low density of permanent weather stations.
(2) The existing network of stations is mainly coastal and therefore non-representative.
(3) A lack of long-term, continuous research.
(4) Confusion about some aspects of the radiation and energy budget.
(5) A need to properly assess the influence of polynyas on meteorology.
(6) A need to improve knowledge of climatic links to permafrost.
(7) Too few strong university-based research groups.
(8) Few active research projects.

Associated with these problems is the lack of a clear northern policy or commitment on the part of the Canadian Government. We claim sovereignty over the Arctic Islands, yet this claim is not supported by a strong dedication to research there. This lack of policy is best exemplified by events surrounding the passage of the United States Coast Guard ship *Polar Sea* through the North-West Passage. A few weeks after this controversial voyage, our company was asked, as suppliers of data-acquisition systems, to quote on a dozen automatic weather stations for deployment along the Passage. this was an immediate *reaction* to the event and not part of government policy to improve weather-monitoring or climatological knowledge along this important sea-route. As long as we have no clearly-defined policies or direction, we will always be reacting to events as they arise, leading to a haphazard development of research priorities.

One exception, and the saving grace as far as arctic research is concerned, is the Polar Continental Shelf Project (PCSP). As stated by Orvig (1981): "The most important project in the Canadian Arctic, in the present context, must be said to be the imaginative Polar Continental Shelf Project which has placed Canadian Arctic research and field operations among the world's best". This agency was created as part of John Diefenbakers's "northern

vision". Without it, research in the Arctic Islands would be impossible. Obviously, PCSP suggests a strong commitment by the government to research in the islands. But this commitment must be questioned when the agency's budget has been continuously decreased since 1984. This decrease in funding was recently reversed as a result of a fortuitous meeting of arctic researchers with the deputy prime minister (press conference with D. Mazankowski, Edmonton, April 8, 1988). What makes the government's commitment to research even more questionable is the contrast between its long-term research funding and its recent plans to spend 8 to 14 billion dollars on nuclear submarines. One of the main arguments used in favour of this plan is arctic sovereignty. This is a complex issue involving many interests, however, the contrast mentioned is too strong to ignore. Obviously, the non-military presence of scientists in the Arctic Islands is a much less expensive alternative. The absence of a strong federal government policy supporting northern research is in part due to a continuing analysis bearing on possible creation of a national northern institute, and in part to the settlement of native land-claims. Once these issues have been properly dealt with, perhaps long-term support for arctic research, not only in meteorology and climatology but for all disciplines, will be established.

FUTURE DIRECTIONS

There have been some positive developments in the past few years that help to balance existing problems. The establishment of an excellent air-quality monitoring station at Alert will provide the necessary database to understand air quality and its influence on climatic change. The initiation of the climate-permafrost monitoring program, albeit confined to the Low Arctic, helps fill a gap left by the late Roger Brown. The creation of readily usable software packages by the Atmospheric Environment Service (Maxwell 1987) makes all forms of arctic meterological, climatological and sea-ice data much more accessible to a wide range of users. Finally, during this past field season, several groups from various disciplines have installed weather-monitoring equipment at various locations in the Arctic Islands. Most of the instruments are on Ellesmere Island (Tanquary Fiord, Lake Hazen, Fosheim Peninsula, Agassiz Ice Field, Cape Herschel and the Princess Marie Bay area), and two were on Bathurst Island. We can only hope that these systems will be operational long enough to

produce climatologically-significant databases. An immediate problem is to coordinate these various databases and archive them so that the data will be accessible to a wide range of users (see Alt and Maxwell, this volume).

CONCLUSIONS

I consider the main problems of meteorology and climatology in the Canadian Arctic Islands to be: the paucity of researchers working in the field, and the paucity of strong university-based research groups. Although some positive steps have been taken, one of the main drawbacks to Arctic research as a whole, is the lack of an explicit, committed northern policy by the federal government.

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THE PLANTS

HIGH ARCTIC ECOSYSTEMS: HOW THEY DEVELOP AND ARE MAINTAINED

L.C. Bliss[1]

Abstract: High Arctic terrestrial ecosystems can be grouped on a landscape basis into polar deserts, polar semideserts, and tundras. The polar deserts support few plant species, and almost no plant production and wildlife. Well-drained substrates prevent water remaining in summer from initiating development of bluegreen algae, cryptogams, and vascular plants. The polar semideserts dominate landscapes in the western Canadian Arctic Islands. These landscapes occur on diverse substrates that support cryptogams into which scattered vascular plants invade. Nitrogen-fixation via bluegreen algae is limited in these ecosystems. Vegetation can support limited numbers of Peary caribou, lemmings and song birds.

Tundra landscapes are the oases of the North. They are dominated by sedge or grass-moss wet meadows. These ecosystems exist only because water remains on the landscape due to blocked drainage by beach ridges or rolling topography. It is here that muskoxen, waterfowl, shorebirds and lemmings abound. Decay of seaweeds and establishment of bluegreen algae on shorelines and in ponds as lands rebounded from the sea, play a significant role in the establishment of these tundra-like ecosystems. This addition of carbon and nitrogen-fixation are of fundamental importance in initiating development of these northern systems.

Résumé: On peut regrouper les écosystèmes terrestres du Haut-Arctique, selon les paysages, en déserts polaires, semi-déserts polaires et toundras. La région des déserts polaires contient fort peu d'espèces de végétation, et presque pas de faune ni de production de plantes. Les substrats bien drainés empêchent les surplus d'eau d'été de générer la croissance des algues bleu vert, des cryptogames et des plantes vasculaires. Dans les îles de l'Arctique canadien de l'ouest, on trouve surtout des semi-déserts polaires. On rencontre ces paysages lorsque divers substrats alimentent des cryptogames qu'envahissent des plantes vasculaires éparses. La fixation de l'azote par les algues bleu vert est restreinte dans ces écosystèmes. Ce type de végétation ne peut nourrir qu'un nombre limité de caribous de Peary, de lemmings et d'oiseaux chanteurs.

On considère les paysages des toundras comme les oasis du Nord. Ils sont recouverts de prairies à laîches ou de prairies humides d'herbes et mousses. Ces écosystèmes ne peuvent exister que grâce à l'eau qui demeure sur le sol, parce que les cordons littoraux ou la topographie ondulée bloquent le drainage. C'est dans ce milieu qu'abondent les boeufs musqués, les sauvagines, les oiseaux de grève et les lemmings. La décomposition des plantes marines et la formation d'algues bleu vert, sur les côtes et dans les mares quand les terres se relèvent, remplissent un rôle significatif dans la création de systèmes comme la toundra. Cette addition de fixation d'azote et de carbone est d'une importance capitale pour déclencher le processus de développement de ces systèmes nordiques.

INTRODUCTION

The Canadian Arctic Islands constitute a vast region that is diverse in topography, geological age, and climate. It should not be surprising that its terrestrial biology is also diverse considering the above factors and its latitudinal extent (61° to 83°N). This entire region falls within the Arctic, the lands that extend climatically beyond the limit of boreal forest and treeline. Large portions of the Canadian Arctic occur on the Northwest Territories mainland and Yukon Territory, but for the purposes of this paper, they will not be discussed.

Over the years, the Arctic has been divided biogeographically into zones and subzones. Porsild (1951) recognized ice desert, rock desert, and tundra; Polunin (1951) and Young

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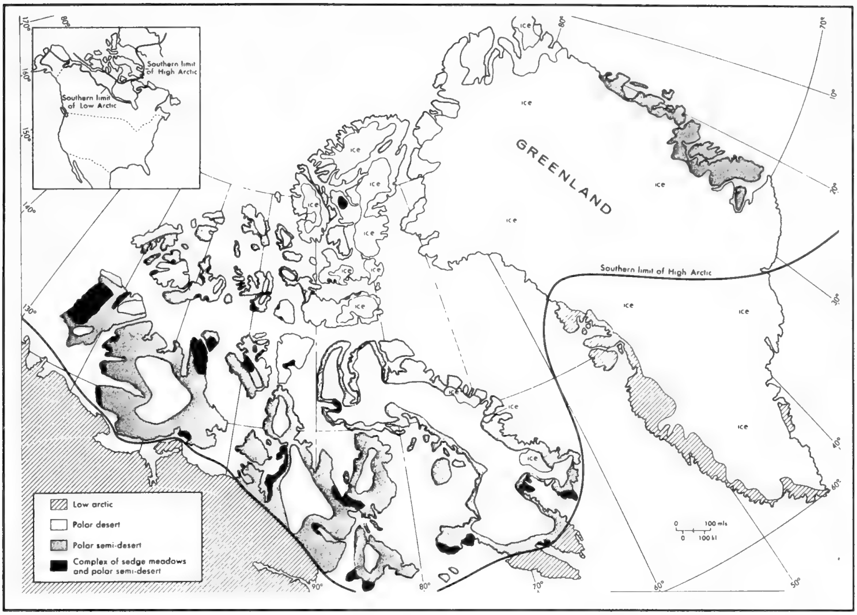

FIGURE 1: The High Arctic of Canada and Greenland illustrating the lack of zonation of the major types of vegetation (from Bliss 1977).

(1971) recognized high, mid, and low arctic zones; and Tedrow (1973) divided the Arctic into polar desert, subpolar desert and tundra. The first three authors used floristics to set the boundaries and Tedrow used soils. Based upon field work and general observations at many locations in the Arctic Islands and at several locations on the mainland, I have divided the Arctic into Low and High Arctic using a variety of environmental and biological data (Bliss 1979, 1981, 1988) (Table 1). With the exception of southern Baffin Island, all of the Canadian Arctic Archipelago falls within the High Arctic (Figure 1). As discussed below a mosaic rather than a zonal pattern seems most appropriate to understanding the biological diversity. This is on contrast with Edlund and Alt (1989) who present bioclimatic zones where temperature is the major factor. Temperature measured as degree-days is very important, but so are water and nutrient status of the soils.

TABLE 1: GENERAL COMPARISON OF ENVIRONMENTAL AND BIOLOGICAL CHARACTERISTICS OF THE LOW AND HIGH ARCTIC WITHIN CANADA.

CHARACTERISTICS	LOW ARCTIC	HIGH ARCTIC
Environmental		
Length of growing-season (months)	3 - 4	1.5 - 2.5
Mean July temperature (°C)	8 to 12	3 to 8
Mean January temperature (°C)	-20 to -28	-25 to -35
Annual mean temperature (°C)	-9 to -12	-12 to -19
Accumulated degree-days above 0°C	600 - 1400	150 - 600
Active-layer depth (cm)		
fine textured soils	30 - 50	30 - 50
coarse-textured soils	100 - 300	70 - 150
Soil pH	mostly 5 to 6.5	mostly 6 to 8
Organic Layer (cm)		
Lowlands	50 - 300+	5 - 50
Uplands	2 - 20	0 - 1
Biological		
Vascular plants (numbers of species)		
Per region or island	150 - 400	40 - 140
Alaska and Canada	700	350+
Plant-cover (%)		
Tundra	80 - 100	80 - 100
Polar semidesert	20 - 80	20 - 80
Polar desert	1 - 5	1 - 5
Plant-height (cm)		
Shrubs	10 - 500	5 - 100
Herbs	5 - 50	2 - 20
Land mammals (numbers of species)	10 - 15	1 - 8
Large mammals	Barren-ground caribou, muskox, moose	Peary caribou, muskox
Nesting birds (numbers of species)	30 - 60	0 - 20
Fishes (numbers of species)	15 - 21	3 - 7

The objectives of this paper are to: (1) present the landscape pattern of biological systems or ecosystems; (2) explain why they occur where they do; (3) suggest how they developed following deglaciation; and (4) discuss their ability to support wildlife.

PHYSICAL ENVIRONMENT

Climate

The macroclimate of the High Arctic is characterized by continuous darkness in mid-winter, with a cover of snow and ice for 9 to 10.5 months, and by continuous light in summer with its growing season of only 1.5 to 2.5 months. In winter a large semi-permanent system of high pressure blankets the Arctic with its very cold, dry air. In summer the arctic high pressure system is weaker with its southern limit paralleling the arctic-boreal forest boundary about 50% of the time (Bryson 1966). Low pressure systems in the Gulf of Alaska and between Baffin Island and Greenland bring increased precipitation to the southern and eastern portions of the High Arctic in summer.

Annual net solar radiation averages 400-600 $MJ/m^2/yr$ over the southern Arctic Islands, dropping to <100 $MJ/m^2/yr$ in northern Ellesmere Island (Maxwell 1981). Solar radiation and the resultant temperature of soils and air greatly influence the development of vegetation. Except for lands above 200-300 m, most snow disappears in mid to late June, by direct evaporation (sublimation) and by melt. Mean monthly temperature in June is often 1° to 2°C at Sachs Harbour (72°N), Cambridge Bay (71°N), Clyde (70°N) and Eureka (80°N). Many other High Arctic stations have mean monthly temperatures near 0°C in June, but July, the warmest month, averages 3° to 8°C at most stations (Environment Canada 1982; Maxwell 1981). Annual precipitation is highly variable over this region, averaging from 200-680 mm along the coast of Baffin Island to 100-150 mm over much of the central and western High Arctic, and to a low of 60 mm at Eureka, Ellesmere Island. Maxwell (1981) has divided the Arctic Archipelago into five climatic regions. Throughout these regions net annual solar radiation and precipitation are more variable than temperature.

Permafrost

An important physical factor that influences biological activity is the presence of permafrost and the shallow layer of thawed soil that forms in summer - the active layer. Permafrost is defined as areas of soil, rock and seafloor where the temperature remains below 0°C for two or more years. All of the Arctic is underlain by permafrost, and within the Arctic Islands it is generally 400 to 650+ m thick. Not all permafrost has a high ice content, usually represented by massive ice-lenses and ice-wedges. These features are more limited in the High Arctic. Due to freeze-thaw cycles and the differential sorting of fine and coarse materials, sorted and non-sorted circles and stripes, raised and depressed-centre polygons, earth-hummocks and solifluction-slopes and steps are often present. Raised-centre and depressed-centre polygons are found in lowlands with fine-textured mineral and peat soils. Stone nets (sorted polygons) and stripes are typical of uplands. These patterned-ground features (Washburn 1956, 1980) influence the distribution of plants and the development of soils.

Some surface features in the High Arctic result from desiccation cracks rather than from ice formation. Many of these polygonal patterns, are only 10-30 cm across compared with the sorted (rock-edged) and non-sorted polygons that are generally 1-5 m across. Soil-hummocks probably result from intense soil churning during spring and fall freezing cycles, although some hummocks result from growth and accumulation of mosses and soil algae. Needle-ice is another important feature of finer-textured soils. The ice forms in spring and fall, but more commonly in the fall, when the soils are wet and relatively warm compared to the cold air at and above the soil surface. Needle-ice lifts the surface soils 1-5 cm and can pull out seedlings and young plants. This greatly reduces plant establishment in some soils. The grasses *Phippsia algida*, *Puccinellia angustata*, and *P. vaginata* have roots that curl. These species appear better adapted to growing in these more active, bare soils (Bell and Bliss 1978; Grulke and Bliss 1988; Sohlberg and Bliss 1984).

The shallow active layer (10-30 cm) of lowland, wet areas with their abundance of bryophytes, sedges, and some grasses greatly limit the vertical development of roots. Better-drained soils of uplands, slopes, and coarse-textured sands and gravels thaw to a greater depth (50-100+ cm) and are warmer in summer. Consequently plant roots may penetrate to deeper levels, and lemmings can develop tunnel-networks for summer. In winter they live in nests constructed of grasses and sedges on the soil surface, but sites where winter

snow is 50 to 150+ cm deep provide more insulation from the very low air temperatures (-30° to -60°C).

Soils

Plant communities and soils are interrelated in the High Arctic, as they are within the coniferous forest and grassland biomes to the south. However within the High Arctic, soil-forming processes are greatly reduced. Shallow peats (Fibrisols), 5-20 cm thick, overlay gleysolic soils in lowlands with their sedge moss or grass-moss communities. These soils are generally neutral to slightly acid and they usually have higher levels of nitrogen. On rolling lands with polar semidesert vegetation of cushion plant-cryptogam or cryptogam-herb communities, soils are Brunisols to Regosols on the former and Regosolic Static Cryosols on the latter sites. Within the barren polar deserts, soils have no horizon development, are neutral to slightly alkaline and usually base-saturated. Nitrogen and phosphorus are very low in these Gleysols and Regosols. Free carbonates are sometimes released from sedimentary rocks or recently uplifted marine sediments nearer to coasts. In these habitats, magnesium and calcium salts effervesce on soil surfaces during brief warm, dry periods in summer. Halophytic species are found in these sites, as well as in shallow coastal lagoons with extremely depauperate salt marshes (Jeffries 1977). Details of High Arctic soils can be found in Tedrow (1977).

EVOLUTION OF HIGH ARCTIC ECOSYSTEMS

Arctic ecosystems are young in terms of geological time. The Beaufort Formation from Banks Island (71°N) to Meighen Island (80°N) contains fossils of mixed coniferous-deciduous forests that date from mid-Miocene to Pliocene age (8-5 million years ago) (Hills *et al.* 1974; see Matthews *et al.*, this volume). Tundra may have occurred farther north and at higher elevations on Axel Heiberg and Ellesmere islands. Plants and animals that now occupy the Arctic are believed to have evolved on the highlands of central Asia and the mountains of northwestern Asia and northern North America (Hoffman and Taber 1967; Yurtsev 1972; Packer 1974). From these centres of origin, plants and animals spread north

and across Beringia (the former land-connection between eastern Siberia and Alaska) to enrich the biota of both continents.

Although arctic ecosystems had their origin several millions of years ago, the present pattern of ecosystems with their limited species-richness have been present only since Wisconsin ice retreat. Thus for lowland areas where isostatic rebound of the land has resulted in sedge-moss, grass-moss tundra systems, or polar semidesert systems of cushion plants-cryptogams and cryptogams-herbs, the ecosystems have been developing for less than 10,000-11,000 years (Bryson *et al.* 1965). On rolling uplands of 50-150 m elevation, the landscapes are probably only 3,000 to 6,000 years old, whereas the lands above 200-300 m have been ice-free for less than 3,000 years in the eastern islands. Many of the most barren lands may have been covered in snow and ice during the Little Ice Age, so colonization by cryptogams and vascular plants is limited to the last 130-430 years (Svoboda 1982).

HIGH ARCTIC ECOSYSTEMS, THEIR STRUCTURE AND FUNCTION

Polar Desert Ecosystems

Polar Barrens

There are thousands of square kilometres (some 44% of the total landscape), especially in the Queen Elizabeth Islands, that are essentially devoid of plants, birds, and mammals. These landscapes occur from near sea level (10-20 m) to uplands above 200-300 m. The basic controls involve the geological substrate, as this influences soil development and retention of water, as well as the length of the snow-free season (1-1.5 months). A thin veneer of rocks often covers the surface, reducing the amount of bare soil where seedlings could establish (Figure 2). Other areas have at least 30-50% bare soil relative to surface rocks. The medium-grained sands to clay-loams are very wet following snow melt, yet are often very dry in the upper 1-3 cm by mid to late July, thus making seedling establishment more difficult.

Woody species are absent from these barren landscapes. Only small rosettes of *Draba, Minuartia* and *Saxifraga*, cushion plants of *Saxifraga* or mat-forming species including

Puccinellia occur as widely-spaced individuals. In a study of 23 sites on six islands, only 17 species of vascular plants and 14 species of lichens and mosses were found. The average number of species at a site was nine. Vascular-plant cover averaged 1.8% and cryptogams only 0.7%. The rest of the surface was bare soil, frost-shattered rocks, and pebbles. The most common vascular plants included *Draba corymbosa*, *D. subcapitata*, *Papaver radicatum*, *Minuartia rubella*, *Puccinellia angustata*, and *Saxifraga oppositifolia*. The most common mosses were *Tortula ruralis* and *Hypnum bambergeri* and the lichens *Thamnolia subuliformis*, *Dermatocarpon hepaticum*, and *Lecanora epibryon* (Bliss *et al.* 1984).

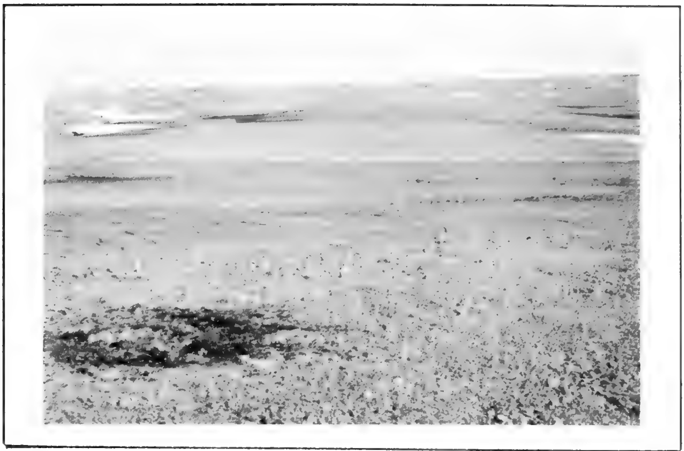

FIGURE 2: The polar desert barrens on Cornwallis Island. The plants in the lower left corner are on an old lemming mound. The species include Papaver radicatum, Saxifraga cernua and Festuca brachyphylla.

Snowflush

The only significant plant cover within the polar barrens is found in the meltwater channels below large snowbanks. These snowflush communities are very conspicuous, yet they occupy only 3-5% of the landscape. Many more species were sampled in these habitats with meltwater present all summer (30 species of vascular plants and 27 species of mosses and lichens) in the 12 sites sampled on three islands. Plant cover was also much greater within the snowflush communities; 18.5% bryophytes, 9% vascular plants, and 8% lichens. Vascular plants occur on moss-mats, usually as scattered individuals (Figure 3). In some sites the graminoids *Eriophorum triste* or *Alopecurus alpinus* were the most important species; in others *Saxifraga oppositifolia*, *Papaver radicatum*, *Draba corymbosa*, *Minuartia rubella*, and *Phippsia algida* dominated as scattered plants. Bluegreen algae (Cyanobacteria) were

always found in the moss mats, so the ability to fix nitrogen is present in these habitats. The stripes and polygonal troughs contain the mosses *Orthothecium chryseum*, *Ditrichum flexicaule*, *Drepanocladus revulens*, *Schistidium holmenianum*, and *Hypnum bambergeri*. The lichens *Dermatocarpon hepaticum* and *Lecanora epibryon* were the only ones of importance. With the exception of *Phippsia algida* and *Alopecurus alpinus*, almost all vascular plants were found on the moss-mats, microsites that are always moist and contain more nutrients. *Salix arctica* was found at only one site, a steep slope facing south, and therefore a warmer site.

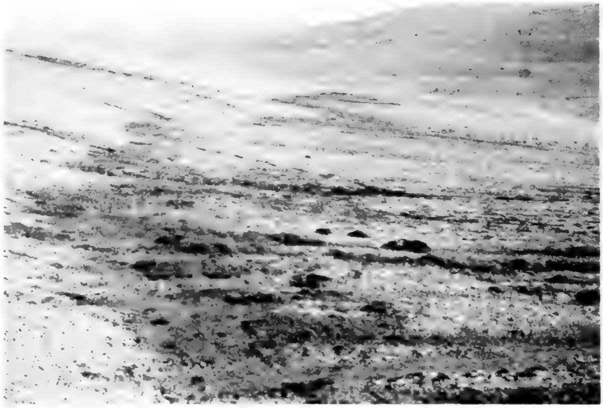

FIGURE 3: Snowflush site within a polar desert barren on Cornwallis Island. Within the moss-mats are scattered plants of Alopecurus alpinus, Phippsia algida, Saxifraga cernua and Papaver radicatum.

Within these barren lands, collared lemming colonies are rare, and most colonies observed were inactive. Due to manuring, plants were always abundant on these slightly-elevated sites. They commonly include *Papaver radicatum*, *Alopecurus alpinus*, *Poa arctica*, *Saxifraga cernua*, and *Cerastium alpinum*.

Polar Semidesert Ecosystems

In addition to the barren polar deserts and lands covered with ice caps and glaciers (10% of the total area), there are vast areas of land that have 5% to 25% cover of vascular plants. Lichens and bryophytes contribute an additional 20% to 80% cover in many areas. Vascular plants are smaller in size (3-10 cm) than the same species (10-30 cm) in the Low Arctic of mainland Canada and northern Alaska, the result of a more severe environment. Root systems of these plants are also smaller. The two major community

types are cushion plant-cryptogam and cryptogam-herb. Polar semideserts cover about 40% of the lands of the Arctic Islands.

Cushion Plant-Cryptogam

Large mats of *Dryas integrifolia* with associated species of *Salix arctica, Saxifraga oppositifolia, S. caespitosa, S. cernua, Papaver radicatum, Draba corymbosa*, and several species of *Stellaria* and *Minuartia* occupy rolling uplands and gravelly raised-beaches (Figure 4). Scattered plants of *Carex rupestris, C. nardina, Alopecurus alpinus*, and *Luzula confusa* are also present. The common lichens *Thamnolia subuliformis, Dermatocarpon hepaticum, Lecanora epibryon*, and the mosses *Hypnum bambergeri* and *Tortula ruralis* generally add 30% to 60% cover. Communities of this general type have been described by Brassard and Longton (1970), Svoboda (1977), Reznicek and Svoboda (1982), Sheard and Geale (1983), and Bliss *et al.* (1984).

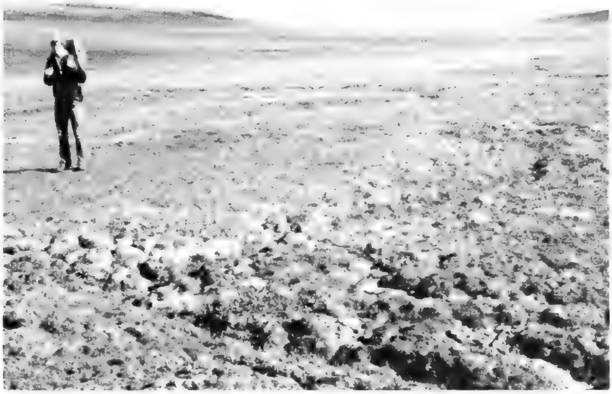

FIGURE 4: Rolling upland near Thomson River, northern Banks Island, within a cushion plant - cryptogam plant community. The dominant cushion-plants are Dryas integrifolia and Salix arctica with smaller amounts of Carex nardina, Oxytropis arctica, and Parrya arctica.

Peary caribou, collared lemming, ptarmigan, Snow Bunting, Black-bellied Plover, and Baird's Sandpiper are commonly found in these lands, although in low numbers because of the limited forage and invertebrates to feed upon. This community and the cryptogam-herb community provide important habitat for caribou.

Cryptogam-Herb

Communities of lichens and mosses with scattered clumps of herbaceous plants and graminoids often cover the rolling hills on the western Queen Elizabeth Islands (Figure 5). The soils are sandy to clay-loam in texture. Vascular plants generally contribute 5% to 20% cover and cryptogams 50% to 80% cover. *Papaver radicatum*, *Cerastium alpinum*, *Draba corymbosa*, *Juncus albescens*, and three to five species of *Saxifraga* are the most common forbs. The dominant graminoids include *Alopecurus alpinus*, *Luzula confusa*, and *L. nivalis*.

FIGURE 5: A cryptogam-herb community on King Christian Island. The dominant vascular plants are Alopecurus alpinus, Luzula confusa, Draba bellii, Papaver radicatum and several species of Saxifraga. Mosses and crustose lichens are also abundant.

Some of the more common mosses include *Ditrichum flexicaule*, *Pogonatum alpinum*, *Polytrichum juniperinum*, *Aulacomnium turgidum*, *Rhacomitrium sudeticum*, *Tomenthypnum nitens*, and *Schistidium holmenianum*. In clay-soils that are wetter in summer, the liverwort *Gymnomitrion corallioides* is often abundant. Common species of lichens include *Lecanora epibryon*, *Lepraria neglecta*, *Dermatocarpon hepaticum*, *Cladonia delisei*, *C. gracilis*, *Cetraria cucullata*, *C. nivalis*, and *Dactylina ramulosa* (Bliss and Svoboda 1984). There is often a thin, black crust of lichens, mosses, and bluegreen algae called "patena". We believe this crust is important in fixing nitrogen in soils that are low in nitrogen and phosphorus.

Seedlings of vascular plants are found on a variety of microsites, but their survival to adults is much more common on moss-mats and to a lesser extent lichen surfaces and desiccation-cracks where mosses are more abundant (Sohlberg and Bliss 1984). Crustose lichens are not as effective as moss-mats in reducing evaporation from moist surfaces.

Lichens are more effective in reducing evaporation when surface soils are dry (Addison and Bliss 1980). This helps to explain why seed germination and seedling survival is not abundant in these communities (Bell and Bliss 1980). Seeds are transported over the snow and, in general, the number of seeds trapped in the lower layers of snow in spring reflects plant density and seed production within these cryptogam-herb communities (Grulke and Bliss 1983).

Data on plant/water relations of several species also help explain their distribution patterns. *Luzula confusa* is confined to moist soils, and is not found in the dry soils (upper 3-5 cm) of exposed slopes and ridges within the cushion plant-cryptogam and cryptogam-herb plant communities. Nor is this species found in the barren polar deserts. Rates of photosynthesis drop significantly with increased leaf water potentials of -0.7 MPa (Addison and Bliss 1984). In contrast, *Phippsia algida* and *Puccinellia vaginata* are not severely drought-affected at leaf water potentials of less than -2.0 MPa (Grulke and Bliss 1988). Both species grow in bare soils, and *Phippsia* also is found within mats of cryptogam-herb communities.

Mammals and birds occur in these polar semidesert landscapes, but species are few and densities are low. Collared lemmings (*Dicrostonyx groenlandicus*) occur as sparse colonies. Many of the "lemming gardens" observed are abandoned in a given summer. No studies have been conducted on lemming densities in the central and western islands. At Truelove Lowland on Devon Island, lemming densities averaged 1.8/ha on the cushion-plant communities of beach-ridges and 3.3/ha in the lusher vegetation of ice-core polygons. These animals consumed mostly *Dryas integrifolia*, *Salix arctica*, and *Saxifraga oppositifolia* (Fuller *et al.* 1977). In the northwestern islands where rosette-forbs and tufted-graminoids are more common (cryptogam-herb plant communities), I have observed that a greater mixture of species is consumed including *Alopecurus alpinus* and *Poa arctica*.

Muskoxen (*Ovibos moschatus*) are seldom observed in polar semideserts of the western Queen Elizabeth Islands because of limited forage. However Peary caribou (*Rangifer tarandus pearyi*) occur in small numbers in the northwestern islands, but are more common on Melville, Banks, Victoria, and Prince of Wales islands. These animals are most commonly observed in the rolling uplands dominated by cushion-plant communities.

Arctic fox (*Alopex lagopus*) and arctic wolf (*Canis lupus*) are seldom found in these landscapes, presumably because of the lack of food to support them. Arctic hares (*Lepus

arcticus) are rare unless *Salix arctica*, their preferred food, is abundant. Feeding observations on the Truelove Lowland, Devon island showed that *Salix arctica* and *Pedicularis* spp. were the preferred foods (Riewe and Speller 1972). The largest hare populations are on Ellesmere and Axel Heiberg islands where arctic willow is abundant.

Birds are seldom observed in the Queen Elizabeth Islands unless ponds and lakes are present. The most common species with breeding populations in uplands include: Snow Bunting (*Plectrophenax nivalis*), Arctic Tern (*Sterna paradisaea*), Baird's Sandpiper (*Erolia bairdii*), and Black-bellied Plover (*Squatarola squatarola*). Long-tailed jaeger (*Stercorarius longicaudus*), and Rock Ptarmigan (*Lagopus mutus*), are present but in low numbers. Although these species nest in upland sites or rock outcrops with cushion-plants, dwarf-heath or cryptogam-herb communities, most species feed extensively in graminoid-moss meadows where insects are more common (Pattie 1977, Freedman and Svoboda 1982). Breeding-bird densities are low within the High Arctic (2 to 33 pairs/100 ha) compared with the Low Arctic of mainland Canada (60 to 200 pairs/100 ha) (see Freedman and Svoboda 1982). In more barren landscapes with mostly polar-semidesert vegetation, limited data indicate 2 to 5 pairs/100 ha is near the upper end of the density scale.

Tundra Ecosystems

Biologically the most important ecosystems in the Arctic Islands are the scattered lowlands often called the oases of the High Arctic (Bliss 1977, Svoboda and Freedman 1980, 1989). These heterogenous landscapes contain: lush sedges, grasses, and mosses; ponds and small lakes; and often beach-ridges and other sites that are better drained with cushion plant-cryptogam and dwarf shrub-heath communities. Wetland ecosystems occupy only 1-2% of the landscape in the Queen Elizabeth Islands, but are more common in the southern islands (Table 2). In addition to these graminoid-moss communities there are limited areas of dwarf shrub-heath, cottongrass tussock, and tall or medium shrub communities. It is these communities, although very limited in extent, that have enabled some authors to refer to these lands as Mid or even Low Arctic (Ritchie *et al.* 1987). Because most of the land is covered with cushion plant-cryptogam vegetation and polar desert, and since bird, fish, and mammal faunas are comparable to those of the northern islands, it seems only appropriate to consider all of the Arctic Archipelago as High Arctic.

TABLE 2: ESTIMATED LANDSCAPE AREAS WITHIN THE CANADIAN ARCTIC ARCHIPELAGO.

LANDSCAPE-TYPE AND PERCENTAGE				
REGION	MEADOW	POLAR SEMIDESERT	POLAR DESERT	ICE
Queen Elizabeth Islands	1	25	49	25
Southern islands	8	47	43	2
Arctic Archipelago	6	40	44	10

Graminoid-moss Tundra

The only common tundra-like vegetation in the Arctic Islands is the wet sedge-moss or wet grass-moss type (Figure 6). In the southern and eastern islands, communities of *Carex stans* and *C. membranaceae* predominate with lesser amounts of *Eriophorum triste, E. scheuchzeri, Dupontia fisheri*, and *Alopecurus alpinus*. There are very few associated forb species. *Salix arctica* and *Dryas integrifolia* occur in microsites that are better drained, such as moss-mounds and rocky areas. These communities occur only where drainage is impeded along river terraces, small valleys, and coastal lowlands with gravelly beach-ridges (relicts of old shoreline features). Communities with these characteristics have been described from Banks and Victoria islands (Bliss and Svoboda, unpublished manuscript), Devon Island (Muc 1977), Ellesmere Island (Freedman *et al.* 1983), and Bathurst Island (Sheard and Geal 1983). In the northwestern islands the sedges are generally absent, replaced by *Dupontia fisheri* (Figure 7), and to a lesser degree *Alopecurus alpinus* with *Pleuropogon sabinei* in shallow ponds (Bird 1975, Bliss and Svoboda 1984). Bryophytes are abundant in these habitats including *Tomenthypnum nitens, Campylium arcticum, Orthothecium chryseum, Ditrichum flexicaule*, and *Cinclidium arcticum*. Lichens are sparse but the cyanobacteria *Nostoc commune* is very common and is important in fixing nitrogen.

Muskox feed in these wet meadows throughout the year, but the meadows become most critical for winter grazing. During the long, cold winter when all surfaces are covered with snow and ice, these localized "hot spots" or "oases" with their complex of sedges and grasses are essential forage habitat (Hubert 1977). Feeding cycles are 4-6 hours in summer but a

FIGURE 6: Sedge-moss meadow on the Truelove Lowland, Devon Island. Carex stans is the dominant vascular plant with a few scattered Pedicularis sudetica and Salix arctica.

FIGURE 7: Small meadow of Dupontia fisheri near the Hoodoo River, Ellef Ringnes Island.

bit shorter in winter. On average they remove 7% of the aboveground forage within sedge-moss meadows per year. However, in select meadows where they concentrate in winter, 15-20% of the forage is removed. Summer forage has a high protein-content (17-21%) and although it is much lower in winter (6-9%), the protein levels are higher than in many temperate graminoids in winter. Assimilation efficiency of these animals on the Truelove Lowland, Devon Island was estimated to be 84% in summer and 66% in winter, important adaptations to these severe arctic environments (Hubert 1977).

In the eastern and southern islands and on Melville Island relatively large areas exist where there is a mosaic of wet sedge-moss meadows and rolling uplands with cushion plant-cryptogam or less commonly, cryptogam-herb communities (Figure 8). There appears to be little competition for food or space between Peary caribou, that generally occupy the uplands, and muskoxen in the lowlands (Parker and Ross 1976; Thomas and Edmonds 1984; Gray 1987). Caribou graze on the upland graminoids (grasses, sedges, rushes), arctic willow, lichens, and flower-stalks of a variety of forbs but especially *Papaver radicatum* (Wilkinson *et al.* 1976; Thomas and Kroeger 1980). In contrast, muskoxen feed primarily in lowlands both summer and winter, based upon rumen samples (Wilkinson *et al.* 1976). In summer muskoxen also feed in more sparsely-vegetated landscapes (Hubert 1977; Gray 1987).

FIGURE 8: Sedge-moss meadows along the Thomson River, Banks Island, with cushion plant-cryptogam community in the uplands (foreground).

Ponds and lakes are always associated with graminoid-moss meadows, and it is these habitats in which we find shorebirds and waterfowl. Red-throated Loons (*Gavia stellata*),

Oldsquaw (*Clangula hyemalis*), Common Eider (*Somateria mollissima*), King Eider (*S. spectabilis*), and Arctic Tern (*Sterna paradisaea*) nest near these water bodies. Parasitic Jaeger (*Stercorarius parasiticus*), Long-tailed Jaeger (*Stercorarius longicaudus*), White-rumped Sandpipers (*Erolia fusicollis*), and Lapland Longspurs (*Calcarius lapponicus*) commonly nest in these wet meadows on the Truelove Lowland (Pattie 1977). Many of these species also nest in comparable habitat farther north on Ellesmere Island (Freedman and Svoboda 1982; Savile and Oliver 1964). Snow Buntings (*Plectrophenax nivalis*) are usually the most abundant species in these lowlands (Pattie 1977; Freedman and Svoboda 1982).

The most common predators, arctic fox, jaegers, and Snowy Owls (*Nyctea scandiaca*) are commonly found in these lowlands where there is a greater abundance of lemmings and nesting birds.

Dwarf Shrub-Heath Tundra

Heath communities are best developed on southern Baffin Island, although small areas of heath are found on Victoria Island (Polunin 1948; Bliss and Svoboda, unpublished manuscript). *Cassiope tetragona* predominates, but limited amounts of *Vaccinium uliginosum* spp. *microphyllum*, *Salix herbacea*, *S. arctica*, *Luzula nivalis* and *L. confusa* also occur. On Devon and Ellesmere islands, small areas of heath are found, usually with *Cassiope tetragona*, *Dryas integrifolia*, and *Salix arctica* dominating (Brassard and Longton 1970, Bliss *et al.* 1977, Freedman *et al.* 1983). These communities generally occur in and near rocky areas where snow remains until early July. Mosses and lichens are abundant at these sites.

Other Tundra Communities

There are small areas of cottongrass tussock and tall shrub-tundra in the southern islands. These communities are closely related to those of the Low Arctic, but here the species richness is low and shrub-height is greatly reduced. Along rivers and near lakes and ponds are low thickets (0.5-1.5 m) of *Salix alaxensis*, *S. pulchra*, and *S. lanata* (Kuc 1974; personal observation).

Salt-marshes occur along a few coastal areas where stable surfaces of sand, silt, or even bedrock occur. *Puccinellia phryganodes* dominates with lesser amounts of *Carex ursina*, *Cochlearia officinallis*, and *Stellaria humifusa* (Jeffries 1977; Thannheiser 1975). These coastal

brackish marshes are always small in area due to the limited tidal amplitude, shore-ice that remains into July, and a general lack of sands and silts favourable for plant establishment.

PRODUCTIVITY COMPARISON OF HIGH ARCTIC ECOSYSTEMS

From the above discussion, evidently only those lands with more abundant vegetation can support a diversity of wildlife in the High Arctic. Although we have no detailed data for the polar barren and cryptogam-herb ecosystems, plant-production data give some idea of their ability to support birds and mammals. Data from Truelove Lowland clearly show that the sedge-moss meadows are much more productive than the cushion plant-cryptogam systems on the gravelly raised-beach ridges (Table 3). It is these latter communities that are more common in the southern and eastern Arctic Islands and over extensive areas of Melville Island.

Large Herbivores - Peary Caribou and Muskox

Peary caribou (*Rangifer tarandus pearyi*) occur throughout the islands with the exception of Baffin Island where barren-ground caribou (*R. tarandus groenlandicus*), typical of the Arctic mainland occurs (Banfield 1974). Muskoxen (*Ovibos moschatus*) are not found on Baffin Island and only in very low numbers, if at all, in the most northwestern islands (Ellef Ringnes, King Christian, Amund Ringnes, Brock, Borden, Mackenzie King, Prince Patrick and Lougheed). Populations are largest on those islands that have a great amount of forage, mostly wet graminoid-moss meadows and patches of arctic willow, as discussed earlier.

Accurate estimates for the number of Peary caribou and muskoxen are difficult to obtain, and their numbers fluctuate widely. An aerial survey in 1961 estimated 24,300 caribou in the western Queen Elizabeth Islands (Tener 1963), but Miller (1978) reported only 2,700 animals in 1974. This latter estimate followed the severe winter of 1973-1974, when large numbers of caribou and muskoxen died due to icings at the soil-surface, which can eliminate foraging over large areas. Deep winter snow (>50 cm) can also be an important cause of population crashes, by preventing successful cratering for vegetation by muskoxen (Hubert 1977). The general decline in population from 1961-1973 appears to

TABLE 3: ESTIMATED ABOVEGROUND PHYTOMASS, NET ANNUAL PLANT PRODUCTION (NPP), AND PERCENT FORAGE CONSUMED BY CARIBOU AND MUSKOXEN IN HIGH ARCTIC ECOSYSTEMS.

PLANT COMMUNITY	AREA (km)²	ABOVEGROUND PHYTOMASS (t/km²)	NET PLANT PRODUCTION (t/km²)	TOTAL NPP ON 1000 KM² (t/km²)	NPP CONSUMED (%)	FORAGE CONSUMED on 1000 km² (t/km²)
SOUTHERN AND EASTERN ISLANDS						
Low-shrub	5	300- 500	70-100	350- 500	10	35- 50
Wet sedge-moss	60	700-1,000	50- 75	3,000- 4,500	7	210-315
Cushion-plant	280	100- 750	15- 50	4,200-14,000	3	126-420
Polar barrens	655	1- 100	1- 2	------	-----	-----
Total	1000	1,101-2,350	135-226	7,550-19,000	-----	371-785
NORTHWESTERN ISLANDS						
Cryptogam-herb	550	200-2,000	5- 10	2,750- 5,500	2	55-110
Wetgrass-moss	30	500- 800	20- 30	600- 900	5	30- 45
Polar barrens	420	1- 100	1- 2	------	-----	-----
Total	1000	701-2,900	26- 42	3,350-6,400	-----	85-155

TABLE 4: DAILY FORAGE CONSUMPTION AND MEAN BODY WEIGHT FOR ARCTIC HERBIVORES.

SPECIES	DAILY FORAGE CONSUMPTION (% LIVE WT)		MEAN VALUE USED (%)	MEAN BODY WT (kg)	REFERENCES
	Summer	Winter			
Peary caribou	-------	-------	2.2	50	------------
Muskox	1.7-2.2	1.3-1.7	2.2	180	Hubert (1977)

have resulted from low birth-rates and calf-survival (Parker *et al.* 1975). Predation by wolves and polar bears appears to be a minor cause of death, especially for muskoxen (Gray 1987).

Muskox numbers also fluctuate in relation to winter weather and forage-availability. Hubert (1977) reported a density of 0.9 animals/km^2 on five lowlands in northeastern Devon Island. Lower numbers have been sighted on aerial surveys in the mid-1980s (Arctic Institute of North America, unpublished data; see Pattie, this volume). Aerial surveys in 1979-1980 resulted in estimates of 19,300 muskoxen on Banks Island (Vincent and Gunn 1981), but only 12,000 animals on Banks and Victoria islands were estimated in 1980 by Jakimchuk and Carruthers as reported by Gunn (1984). Accurate surveys are difficult to achieve over such large areas, especially when most muskoxen and caribou occur in the limited areas of more lush vegetation.

Landscapes and Estimated Herbivore Carrying-Capacity

To calculate animal carrying-capacity and density, different modelling approaches have been used. Some use ecological efficiencies of the herbivores. Others have used animal density as the driving force. The larger database on plant phytomass and plant production and daily food requirements of large herbivores is believed to give more accurate estimates. The latter approach has been used to estimate past animal density in the Alaskan part of Beringia 25,000 to 11,000 years ago (Bliss and Richards 1982), the Bluefish River area in the Yukon 15,000 to 12,000 years ago (Ritchie 1984), and for modern arctic large mammals of North America (Bliss 1986).

Here I have used estimates of aboveground phytomass, net annual plant production (aboveground), average forage-utilization rates (daily) for a ruminant (2.2%/d of mean body weight), and assumed plant communities on the landscape.

Two major landscapes are considered; one in the southern (Banks, Victoria, Prince of Wales, Baffin) and northeastern Arctic Islands (Axel Heiberg, Ellesmere, Devon), and a second one in the northwestern islands. Peary caribou and muskoxen browse the low shrubs (only Banks, Victoria, Baffin islands) and graze the graminoid-moss, cushion plant-cryptogam and cryptogam-herb communities, but at different intensities. For each landscape I have assumed 1000 km^2 with representative patterns of plant communities and assumed foraging-patterns of the two herbivores (Figure 9). Low willow shrubs (1-1.5 m) are assumed to grow only along streams, rivers, and at a few wet sites in the southern islands. These are

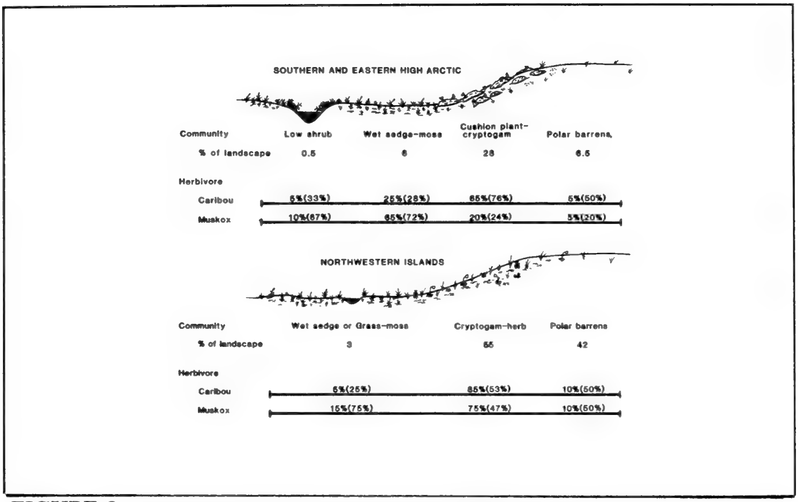

FIGURE 9: Assumed High Arctic landscapes with their dominant plant-communities and large herbivores. The first value is the assumed percentage of the total forage that the herbivore obtains from the plant-community (add across). Numbers in brackets indicate the percentage contribution that a given community contributes to the total diet of each herbivore (add down).

replaced by minor areas of dwarf heath on Devon, Ellesmere, and Axel Heiberg islands. The latter are little used by large herbivores. For the purpose of calculating animal densities, the polar deserts have not been included. They will be factored in when animal densities are estimated for the two major regions.

Calculations of plant community areal extent, aboveground phytomass, aboveground net annual plant production, animal foraging percentages of each community, and annual forage consumed per community are given in Table 3. The rate of mean daily food consumption (2.2% of mean body weight) and mean body weight for muskoxen (180 kg) are taken from Hubert (1977). I have assumed a mean body weight of 50 kg and also a 2.2% daily foraging rate for caribou (Table 4). Given the assumptions of forage available for harvest (Table 3), the percentage consumed by each herbivore per habitat (Figure 9), the rate of daily food consumption and mean body weight, it is possible to calculate the maximum herbivore biomass per species for each region (Table 4). For example, muskoxen in the southern islands consume 67% of the low shrub forage (23-34 t) plus 72% of the wet sedge-moss forage (151-227 t) plus 24% of the cushion plant-cryptogam forage (30-101 t), and essentially nothing from the polar desert. This is a total of 204-362 t from this High

Arctic 1,000 km^2 landscape. If muskoxen consume 803% of their live body weight per year (Table 5), a muskox biomass of 25-45 t (204-362 divided by 803% = 25-45) per year is estimated. Comparable calculations for Peary caribou result in an estimated animal biomass of 21-53 t per year. A total plant biomass of 371-785 t/1,000 km^2 is assumed to be harvested by both herbivores per year. Based upon the calculations in Table 6, 420-1,060 caribou and 140-253 muskoxen could be supported on this landscape. These numbers seem very low, but one must remember that only 34% of the landscape contains harvestable vegetation, thus the number of animals supported in those limited lands of sedge-moss meadow (6% of the total landscape) and cushion plant-cryptogam vegetation (28% of the total landscape) in the polar semideserts are actually much higher. The problem rests with the vast areas of polar desert and ice fields (66%).

Based upon the densities of 0.5 caribou and 0.2 muskox/km^2 (Table 6), the southern and eastern islands have a carrying capacity of 254,000 caribou and 14,800 muskoxen. Such numbers have not been reported in modern times, no doubt the product of excessive Inuit hunting, severe winter weather and possibly disease and predation.

Kevan (1974) estimated the muskox population of Banks Island to be 1,200-1,800 animals, and indicated these numbers were higher than previously recorded. Using various data sets from 1961 through 1975, Dickinson and Herman (1979) estimated the muskox population of Banks, Victoria, Prince of Wales, Devon, and Ellesmere islands to be about 8,500 animals. Comparable estimates for Melville, Bathurst, Axel Heiberg and the northwestern islands were about 3,500-4,000 animals.

Similar calculations for the northwestern islands, including Melville Island, result in a harvested plant biomass of 100-185 t/1,000 km^2 that supports a caribou biomass of only 5-10 t and a muskox biomass of 7-13 t (Table 5). Using the average animal weights of 50 kg for caribou and 180 kg for muskoxen and a yearly forage consumption of 803% of mean live body weight, only 100-200 caribou and 39-73 muskox/1,000 km^2 could be supported by these landscapes. Most of the grass-moss meadow vegetation is on Melville Island and thus most of the muskoxen are located there, as animal surveys confirm (Miller 1978). The estimates of 3% wet grass-moss meadow, 55% cryptogam-herb vegetation, and about 42% polar barrens indicate that these landscapes within the western Queen Elizabeth Islands should support approximately 7,500 Peary caribou and 3,750 muskoxen (Table 7). The aerial surveys reported by Miller (1978) estimated 5,200 caribou in 1973 and only 2,700

TABLE 5: ESTIMATED ANNUAL FOOD CONSUMPTION AND HERBIVORE BIOMASS FOR HIGH ARCTIC ECOSYSTEMS UTILIZING THE LANDSCAPE HABITAT OF FIGURE 9.

SPECIES	FOOD CONSUMPTION (% live wt)		FORAGE CONSUMED IN ALL COMMUNITIES (t/yr)	HERBIVORE BIOMASS (t/1000 km²)
	Daily	Annual		
SOUTHERN AND EASTERN ISLANDS				
Peary caribou	2.2	803	167-424	21-53
Muskoxen	2.2	803	167-424	25-45
NORTHWESTERN ISLANDS				
Peary caribou	2.2	803	40- 77	5-10
Muskoxen	2.2	803	60-107	7-13

TABLE 6: HERBIVORE NUMBERS PER 1,000 KM² OF LANDSCAPE BASED UPON HERBIVORE BIOMASS AND MEAN BODY WEIGHT PER SPECIES.

SPECIES	HERBIVORE BIOMASS (t/1,000 km²)	MEAN BODY wt (t)	NUMBERS 1,000 km²	NUMBERS km²
SOUTHERN AND EASTERN ISLANDS				
Peary caribou	21-53	0.05	420-1,060	0.4-1.1
Muskoxen	25-45	0.18	140- 253	0.1-0.3
NORTHWESTERN ISLANDS				
Peary caribou	5-10	0.05	100- 200	0.1-0.2
Muskoxen	7-13	0.18	39- 73	0.04-0.07

in 1974 after severe winter die-off (Miller *et al.* 1975). In 1961 Tener (1963) had estimated24,000 caribou in these western islands. The limiting factors are severe winters with deep-crusted snows and surface-icings and, to a lesser degree, disease and predation. As Miller (1978) mentioned these lands currently support only a fraction of their carrying capacity.

TABLE 7: POTENTIAL LARGE HERBIVORE CARRYING CAPACITY IN THE ARCTIC ISLANDS BASED UPON MAJOR PLANT COMMUNITIES.

REGION AND ANIMAL DENSITY	LAND AREA (km^2)	MAJOR PLANT COMMUNITIES			
		WET MEADOW-CUSHION PLANT COMPLEX	CUSHION PLANT	CRYPTOGAM-HERB	POLAR BARRENS AND ICE
		AREAL EXTENT (km^2)			
Southern and Eastern Islands	1,224,000	74,000	433,000	------	717,000
Northern Islands	123,000	4,000	26,000	45,000	48,000
		POTENTIAL CARRYING-CAPACITY			
Southern and Eastern Islands					
Caribou ($0.5/km^2$)		37,000	217,000	------	------
Muskox ($0.2/km^2$)		14,800	-------	------	------
Northwestern Islands					
Caribou ($0.1/km^2$)		400	2,600	4,500	------
Muskox ($0.05/km^2$)		200	1,300	2,250	------

There are no recent caribou surveys for all of the southern islands. Kevan (1974) estimated 5,300-8,000 caribou on Banks Island and Fischer and Duncan (1976) estimated 4,300 caribou on Prince of Wales Island. Miller (1978) estimated a total of 10,000 to 15,000 animals in the Canadian Arctic Islands in the mid-1970s. Based upon the above calculations, these lands should be able to support 200,000 to 260,000 animals at a density of $0.5/km^2$ in the southern and eastern islands and a density of $0.1/km^2$ in the northwestern islands (Table 7). There are indications that barren-ground and Peary caribou numbered between 20,000 and 100,000 animals on Victoria Island early in the century (see Gunn, this

volume), and that they migrated annually between the mainland and the island. These herds have been extirpated by Inuit hunters over the years (Manning 1960; Miller 1978).

DEVELOPMENT OF HIGH-ARCTIC ECOSYSTEMS

Following ice retreat 6,000 to 9,000 years ago, coastal areas began to rise as the result of isostatic rebound (Andrews 1970; Barr 1971). With the emergence of new land 10 to 100+ m in elevation, and with successive raised-beach ridges that mark old shorelines, relatively level habitats were provided for plant development. The raised-beach ridges slow the lateral movement of snowmelt waters, enabling surfaces to remain wet most of the summer. These coastal lowlands on the northeastern islands, and valley systems on Ellesmere and Axel Heiberg islands, are the major locations for sedge-moss or grass-moss meadows in the Queen Elizabeth Islands. In the southern islands, valleys and lowlands that are inland as well as coastal are dominated by similar meadows with poorly-drained soils and cushion-plant vegetation on slopes and rolling uplands, habitats that are much drier in summer.

In the northwestern islands, wetlands are rare and only those landscapes with finer-textured soils (usually from old marine sediments) are covered with cryptogam-herb meadow vegetation. These landscapes remain moist all summer due to their cover of cryptogams and soil-texture.

In the rolling uplands on most islands, and the plateau regions of the eastern and central islands, there is almost no vegetation except below huge snowbanks with their snowflush effect. The rest of the landscape has only widely-spaced vascular plants with few cryptogams. These uplands without lichens are probably the result of recent permanent snowcover during the "Little Ice Age", 400 to 600 years ago (Svoboda 1982; Edlund 1985).

The key elements that control vegetation development in the High Arctic are presence of water and adequate nutrients. A continuous supply of water enables mosses to develop, which support colonies of cyanobacteria (bluegreen algae) that fix nitrogen. Symbiotic nitrogen-fixing bacteria occur on the roots of species of *Astragalus*, *Oxytropis* and *Lupinus* in the southern islands and on the mainland. Considerable amounts of nitrogen are fixed as a result (Karagatzides *et al.* 1985). However in the Queen Elizabeth Islands and

throughout the entire Arctic Archipelago, nitrogen-fixation by cyanobacteria appears to be the main mechanism. *Dryas integrifolia* occurs in many areas, but it does not fix nitrogen, in contrast with Low-Arctic and high-mountain populations of *Dryas* species.

A few studies now enable us to better assess the role of cyanobacteria in nitrogen-fixation. The methods used in these studies have varied (soil-core incubation time, field vs southern laboratory determination of acetylene-ethylene, and the sophistication of gas-chromatographic instrumentation), but the results give an indication of the magnitude of the process and the mesohabitat control provided by mosses and surface water.

Uplands

On Cornwallis Island a snowflush community of mosses and cyanobacteria had higher nitrogen-fixation rates within the moss-stripes than in the moist, bare soil between the stripes (Table 8). Much higher rates of fixation were reported for isolated temporary pools of water at the base of the hill. Adjacent bare-soil surfaces that lacked any plant-cover had very low rates of fixation (1.2 $\mu g\ N_2/m^2/hr$). Comparable values of fixation were reported for the barren plateau on Devon Island (Table 8).

These data clearly show that nitrogen-fixation rates are directly linked to areas that remain moist to wet in summer, and that cyanobacteria are favoured by moss-mats and shallow pools of water. Such habitats are highly limited in these barren lands, so development of a more extensive plant-cover without significant climate change seems unlikely.

Lowlands and Valleys

Lowland coastal areas have developed in much more favourable topographic positions, where water remains on the landscape for longer periods. Consequently, moss-mats have developed in wetter areas with an abundance of sheet and ball *Nostoc commune* and other groups of cyanobacteria. The data (Table 8) show that drier habitats occupied by cushion plant-cryptogam communities have much lower rates of nitrogen-fixation than do the wetter sedge-moss meadows.

Current research indicates that these coastal lowlands have probably developed in two ways. As the land gradually rebounded from the sea and marine algae washed ashore, the decaying plants were invaded by green algae and sequentially by bluegreen algae

TABLE 8: ESTIMATED RATES OF NITROGEN-FIXATION ($\mu gN_2/m^2/hr$) BASED UPON ACETYLENE REDUCTION BY CYANOBACTERIA AND OTHER BACTERIA IN VARIOUS HABITATS IN THE HIGH ARCTIC.

LOCATION AND HABITAT	NITROGEN-FIXATION ($\mu gN_2/m^2/hr$)	AUTHOR
	POLAR BARRENS $\bar{x}$ ± S.D.	
Devon Island - plateau	1.9 ± 0.5	Jordon *et al.* 1978
Cornwallis Island - beach ridge	1.2 ± 1.9	Baumbraugh 1980
Cornwallis Island - small ponds	23.2 + 23.7	Baumbraugh 1980
Cornwallis Island - snowflush with moss	6.4 ± 8.2	Baumbraugh 1980
Cornwallis Island - snowflush bare soil	3.0 ± 3.6	Baumbraugh 1980
	POLAR SEMIDESERT	
Devon Island - beach ridge	7.2 ± 11.3	Stutz 1977
Devon Island - Wolf Hill	1.5 ± 1.1	Stutz 1977
Devon Island - beach ridge	4.8 ± 1.2	Jordon *et al.* 1978
	TUNDRA SEDGE-MEADOW	
Devon Island - mesic meadow	53.4 ± 21.0	Jordan *et al.* 1978
Devon Island - hummock meadow	24.8 ± 16.8	Stutz 1977
Devon Island - Wolf Hill meadow	6.2 ± 3.4	Stutz 1977
Ellesmere Island - Alexandra Fiord meadow	58.8 ± 8.8[1]	Henry and Svoboda 1986
Ellesmere Island - Sverdrup Pass meadow	51.3 ± 3.9[1]	Henry and Svoboda 1986
	COASTAL MEADOW SEQUENCE	
Devon Island - Puccinellia-algal meadow	1,274 ± 538	Chapin and Bliss 1988
Devon Island - Algal hummocks	239 ± 75	Chapin and Bliss 1988
Devon Island - Dupontia-moss meadow	320 ± 94	Chapin and Bliss 1988
Devon Island - Carex-moss meadow	329 ± 92	Chapin and Bliss 1988

[1] S.E.

(cyanobacteria). Where surfaces remain moist from melting snowbanks upslope, the cyanobacteria are able to form organic soil. These organic substrates are invaded by species of *Draba*, *Saxifraga*, *Cerastium*, *Minuartia* and *Salix arctica*. In wetter shoreline basins, graminoids enter early in the sequence. First, *Puccinellia phryganodes* colonizes while the sites are still brackish, then *Dupontia fisheri* and *Alopecurus alpinus* invade as the soils become deeper (10-20 cm) and less influenced by marine waters. In time, with further development of peaty soils that retain water for longer periods in summer, *Carex stans*, *C. membranacea* and *Eriophorum triste* invade. Cyanobacteria are no doubt an important constituent of all of these communities, both in terms of carbon accumulation and especially in nitrogen-fixation. Data (Table 8) demonstrate the abundance of existing nitrogen-fixation in these coastal communities.

The second method of meadow development relates to cutting off large lagoons with adjacent shallow basins. Over time, with further uplift and partial drainage, hypothetically cyanobacteria develop in the shallow shoreline areas along with mosses. As organic matter accumulates with considerable amounts of nitrogen, grasses and sedges become established and eventually develop into the large, wet meadows found today. This same process of shallow water, organic matter build up by algae and mosses, followed by invasion of graminoids, occurred in mountain valleys and basins inland from the coast of Ellesmere and Axel Heiberg islands in the east, as well as on all of the southern islands. Melting snow on slopes above is an essential component.

The deeper organic soils at the base of beach-ridges, in the transition from a beach-ridge crest to a wet meadow below may result from the stranding of marine algae first, followed by colonization of cyanobacteria and probably *Puccinellia phryganodes*. Because these habitats are well-drained a few days after snowmelt, mosses and cyanobacteria are moist for a much shorter time, so organic matter accumulation is greatly reduced in surface soils and rates of nitrogen-fixation are also much less. One might liken these areas to arrested examples of succession that never will develop a thick organic layer with abundant nitrogen from blue-green algal fixation. Consequently, the cushion-plants of *Saxifraga oppositifolia*, *Dryas integrifolia*, *Salix arctica*, and scattered plants of *Papaver*, *Draba*, and *Minuartia* form a stable community that has little chance of developing into a more mesic habitat because of limited water and nitrogen.

On the northwestern islands, the gentle slopes with finer-textured soils are covered with mosses and lichens in which scattered vascular plants occur. Perhaps these plant-communities are limited in their accumulation of organic matter and nitrogen by the relatively thin mat of mosses. This is controlled by the limited amounts of water retained during spring runoff. I further hypothesize that rates of nitrogen-fixation are limited in these landscapes by the reduced mass of cyanobacteria that can be supported. As with the cushion plant-cryptogam communities of the eastern and southern islands, these cryptogam-herb communities have little chance of further development without important climate change and the retention of surface water for longer periods of time.

In summary, throughout the High Arctic, cryptogams (especially mosses) play a critical role in supporting large amounts of cyanobacteria. Where this occurs in coastal lowlands or mountain-valleys, a deeper organic layer forms that can hold water longer, and this permits the cyanobacteria to fix more nitrogen. The deep, wet, organic soils with their higher nitrogen-levels enable the graminoids to form meadows. These wetland oases with their mosaic of better-drained habitats provide the landscape and plant-community diversity so necessary for the support of muskoxen, Peary caribou, lemmings, and the associated birds. The keys are topographic location, abundant water throughout the summer, and the development of soils relatively rich in nitrogen as a result of cyanobacteria. Thus the High Arctic has a mosaic pattern of ecosystems which cannot be easily divided into latitudinal zones.

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LICHENS IN THE CANADIAN ARCTIC ISLANDS

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Abstract: A summary of early exploration of the Canadian Arctic Islands for lichens is followed by an account indicating the accelerated exploration of the present century. The best known islands for lichens include: Axel Heiberg (149 species), Baffin (331 species), Banks (90 species), Bathurst (117 species), Cornwallis (54 species), Devon (163 species), Ellesmere (186 species), Prince Patrick (123 species), Somerset (50 species), Southampton (135 species), and Victoria (40 species). Of the 968 lichens known from the North American Arctic, 456 are so far known to occur on the Canadian Arctic Islands. Further surveys will improve such figures, especially considering that so many of the islands are unexplored for their lichen flora. Much also remains to be investigated on the ecological relationships and adaptations of the lichens in this part of Canada.

Résumé: Un sommaire des premières explorations des îles de l'Arctique canadien est suivi d'une illustration de la rapidité avec lacquelle elles ont été explorées dans le siècle actuel. Les îles les plus renomées pour leurs espèces de lichens sont: Axel Heiberg (149 espèces), Baffin (331 espèces), Banks (90 espèces), Bathurst (117 espèces), Cornwallis (54 espèces), Devon (163 espèces), Ellesmere (186 espèces), Prince-Patrick (123 espèces), Somerset (50 expèces), Southampton (135 espèces) et Victoria (40 espèces). Des 968 espèces de lichens identifiées dans l'Arctique nord-américain, on en compte actuellement 456 dans les îles de l'Arctique canadien. Des recherches plus poussées devraient améliorer ces chiffres, surtout si l'on considère que la flore des lichens n'a pas encore été étudiée dans un bon nombre de ces îles. Il reste également beaucoup à étudier sur les adaptations et affinités écologiques des lichens dans cette partie du pays.

INTRODUCTION

A polar desert devoid of vegetation and covered by ice may be the popular idea of what the Canadian Arctic Islands are like. In truth, there is a rich lichen flora - even more numerous in species than that of the flowering plants. Long neglected, this group of plants is now becoming the object of intensive research. The opportunities are immense for studies in taxonomy, ecology, and physiology of the arctic lichens, and the progress from a meagre beginning to a richer knowledge is under way.

EARLY EXPLORATION

For a knowledge of the early exploration of the Arctic Islands there is an excellent summary by Lynge (1947) in Polunin's "Botany of the Canadian Eastern Arctic, Part 5".

The earliest expedition to bring back lichens to Europe was that of John Ross in 1818 aboard *Isabella* and *Alexander*. On this voyage only nine lichens were collected from

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unspecified sites on both the east and west coasts of Baffin Island. The specimens were identified by Robert Brown (1819). On Parry's voyage of 1819-1820, *Hecla* and *Griper* penetrated as far as Winter Harbour on Melville Island. Ten lichens were collected on Melville Peninsula along the way by the surgeon, Mr. Edwards, and by Parry. A few lichens were collected by Dr. Sutherland on the 1850 voyage of Captain William Penny on board *Lady Franklin*. The lichens came from Cornwallis Island and "Banks Land" as well as Greenland but were not clearly identified by Churchill Babington (1852). Penny's ship was one of a squadron involved in the Franklin searches.

Sir Francis M'Clintock on board the *Fox* in Baffin Bay and Prince Regent Inlet in 1857, 1858, and 1859 on the Franklin searches) had Dr. David Walker as surgeon-naturalist who collected plants, including lichens, later identified by J.D. Hooker (1861). The lichens were from Somerset and Devon islands. Although Dr. I.I. Hayes collected along Smith Sound in 1861, the 23 lichens were badly determined according to Theodore Fries (1879), and no localities were given.

The earliest report of consequence was by the Swedish lichenologist Fries (1879). It listed 102 lichens, several new to science, based on material collected by Captain H.W. Feilden on the *Alert* and Mr. H.C. Hart on the *Discovery* - members of Nares Expedition of 1875-1876. The Expedition operated mainly in areas of Ellesmere Island then known as Ellesmere Land, Grinnell Land, and Grant Land, as well as Greenland and the shores of Smith Sound.

On the Howgate Polar Expedition (1877-1878) to Cumberland Sound on the east coast of Baffin Island, the Wisconsin naturalist Ludwig Kumlien collected lichens. Some 53 taxa in 29 species were named by Edward Tuckerman of Harvard University. Curiously, when Milton College, Wisconsin, closed its doors in 1982, its museum collections were disposed of to the University of Wisconsin and some Howgate lichen collections, never sent by Kumlien to Tuckerman, turned up unnamed and still in their original field containers.

Seven specimens were collected by Greely's Expedition of 1882-1883 in northeastern Ellesmere Island. The lichens were determined by E. Lehnert, a minister in Washington, D.C. (Lehnert and Greely 1888). It is a wonder that any lichens at all were collected on this primarily military expedition which involved a dash toward the pole, but which resulted in the death of all but seven expedition members.

Thirty-seven species of lichens were collected on the Norwegian Gjøa Expedition (1903-1907) led by Amundsen. They were mainly from islands west of Gjøa Haven, King William Island, and were determined by Lynge (1921). The Second Norwegian Arctic Expedition under Otto Sverdrup in the *Fram* (1891-1902) worked mainly on Ellesmere Island. A Swedish botanist, H.G. Simmons, on this expedition made a large collection of plants including mosses and lichens. Lichens collected on the expedition were entrusted to Dr. O.V. Darbishire of Oxford University who determined 158 species, and augmented the total in his report with a listing of lichens previously collected from Greenland, Iceland, etc. Unfortunately Lynge, the renowned arctic lichen specialist, considered the determinations to be unreliable. The specimens have never been redetermined completely, since many have been distributed to a variety of herbaria.

J.D. Soper, a naturalist with the Eastern Arctic Patrol of 1923 and several patrols thereafter, collected mosses and lichens on Baffin, Ellesmere and Devon islands. These are in the lichen collections at the National Museum of Natural Sciences (CANL).

In 1931 Nicholas Polunin, well known for publications on arctic flowering plants, collected on Akpatok Island in Ungava. This collection of 35 species was determined by Annie Lorrain Smith and published in 1934.

The Eastern Arctic Patrols of 1934 and 1936 yielded a large number of lichens collected by Nicholas Polunin. They came from Ellesmere, Devon, Philpots, Baffin and Southampton islands, as well as other northern localities. The 1934 collections are in the British Museum (Natural History), the 1936 collections being in the Farlow Herbarium, Harvard University. Lynge's publication on these collections lists 275 species, and is an outstanding summary of lichens to that date in the eastern Canadian Arctic.

Father Arthème Dutilly, Naturaliste des Missions de l'Arctique, collected at several places in northern Canada after 1933. He visited localities on Baffin Island in 1936, (Arctic Bay, Cape Dorset, Clyde River, Pangnirtung, and Lake Harbour), Craig Harbour on Ellesmere Island, Dundas Harbour on Devon Island, and Southampton Island. In 1937, he reached Igloolik Island, and in 1938 Winter Island. His lichens were determined by Lynge (1939). Of the 88 lichens, some 63 were from the Canadian Arctic Islands.

Although the number of specimens collected on these early expeditions were small in the light of modern expectations, the immense difficulties faced on those expeditions

should be remembered. The collection of scientific material was mainly by chance. Expeditions focused on exploration and mapping - studies of magnetism, tides, and astronomical observations seemed to be the principal tasks. Perhaps their training in botany as applied to medicinal plants gave early expedition doctors the incentive to collect plants. Lichens were considered too lowly to be of much interest to plant collectors then, despite their dominance in the arctic vegetation. Furthermore, there was the problem of the paucity of storage-space on the small expedition vessels. Perhaps scurvy among crews and officers sapped their energies, which otherwise might have been used for scientific studies and collecting. It is a wonder that any specimens at all reached Europe, considering the problems of man-hauling sledges in many of the early expeditions. Polunin (1940) summarizes the situation plainly and poetically:

> "First thoughts should, perhaps, go to the long line of stoic earlier explorers mentioned above, who ventured forth they knew not where - all too often never to return. Those who were successful in many cases brought back pioneer collections of inestimable value to science, or gained immortality by having their names written on the maps of new regions; those who perished are too often forgotten. With their frail cockle-shells of sailing sloops, hand-drawn sledges, and scurvy-bringing salt foods they one and all helped to pave the way for the modern scientific investigator, whose lot is infinitely more comfortable and less hazardous."

RECENT EXPLORATION

The entry of air transport greatly increased accessibility and scientific activity in the Canadian Arctic Islands. After the Second World War, scientific expeditions could reach quickly and deeply into uncharted areas of the Canadian Arctic. Although collectors were still rarely lichenologists, and their collections were made as a sideline to other official activities, the specimens they gathered have immensely enriched our knowledge of Arctic Islands vegetation.

I attempt here to summarize the wealth of new material that has flowed in to increase our knowledge of the lichen flora of the islands. In some cases I know only the name of the collector and the island(s): in others I can give more detail. Just as with

the earlier collectors, most visited the Arctic Islands for other purposes, but the lichens captured their interest and were collected for study by others. Their collections thus became an indispensable source of information on many of the islands. Among the few professional lichenologists who have visited the Canadian Arctic Islands are: Roland Beschel, Charles Bird, I.M. Brodo, Mason E. Hale, J.W. Thomson, and W.A. Weber. The most productive collector of lichens in the Canadian Arctic is George W. Scotter (Canadian Wildlife Service) who has ranged widely across the North in connection with caribou and other wildlife studies, as well as on Parks Canada surveys. His collections have usually been studied by several lichenologists including: Teuvo Ahti (Helsinki), C.D. Bird (Calgary), I.M. Brodo and P.Y. Wong (Ottawa), J.W. Thomson (Wisconsin), and W.A. Weber (Colorado).

The post-Second World War period is probably best covered chronologically. The earliest of these collections was made by the colourful polar expert Alan Innes-Taylor (see Marshall 1984). While Innes-Taylor was a member of a Canadian-United States weather station group during 1947 and 1948 he brought back specimens of 88 species of lichens from Axel Heiberg, Baffin, Bathurst, Cornwallis, Devon, Ellef Ringnes, Ellesmere, and Ward Hunt islands (Thomson 1960). The specimens were the first from some of the remote islands of the archipelago, and are in the lichen herbarium of the National Museum of Natural Sciences (CANL).

In 1969 H.B. Collins collected a few lichens (CANL) on Cornwallis Island. In the same year W.K.W. Baldwin, with the Foxe Basin Expedition on Solomons Temple Islands and islands in James Bay, collected some 81 specimens (CANL) of arctic rock-lichens in connection with spectroscopic examination of rocks.

During 1950 several collectors worked in the islands. A.H. Lawrie collected (CANL) on Ellesmere, Cornwallis, and Devon islands. Stuart D. MacDonald collected some 36 specimens (CANL) on Ellesmere and Prince Patrick islands. R.L. Christie and G. Hattersley-Smith brought back 32 lichens (CANL) from Ellesmere and Ward Hunt islands. The largest collections were made by Mason E. Hale at several localities on Baffin Island. Hale (1954) accompanied the Arctic Institute of North America Expedition to 11 localities on Baffin Island, collecting 257 species (WIS, CANL, US), the largest number reported from the Arctic Islands to that date. J.C. Ritchie collected 57 species (WIS) on Southampton Island in 1954 (Thomson 1956). In 1955, the bryologist R.M.

Schuster collected 108 lichen species (WIS, CANL) near Alert, Ellesmere Island (Schuster *et al.* 1959).

During 1957 John M. Powell collected 38 species (CANL) near Lake Hazen, northern Ellesmere Island, and R. Thorsteinsson brought back lichens (CANL) from Meighen and Mackenzie King islands. About this period, D.B.O. Savile collected (CANL) on Ellef Ringnes Island. During 1959 C.R. Harington collected approximately 65 species (CANL) on Mackenzie King, Cornwallis, and Ellesmere islands - some in collaboration with J.S. Tener.

During the International Botanical Congress (Montreal, 1959), an outstanding field trip by air included the Canadian Arctic Islands (Leonard 1961). Two lichenologists, W.A. Weber (University of Colorado; Figure 1) and J.W. Thomson (University of Wisconsin) participated. Unfortunately, the lichens collected on this trip to Baffin, Cornwallis (Figure 2), Victoria, and Southampton islands, as well as Ungava localities are still being studied. However the work is nearing completion.

In 1960 Alex Dzubin collected (WIS) 14 lichens on Banks Island and 18 on Victoria Island. During 1961 C.R. Harington collected (CANL) on Mackenzie King and Cornwallis islands. In 1964 D.E. McAllister collected six lichens (CANL) on Prince Patrick Island.

During 1964, John Lambert while surveying plant communities on southwestern Banks Island, found a second stand of *Teloschistes arcticus*. This is a lichen which was collected by Parry on Melville Island and described as *Borrera aurantiaca* (Brown 1824, Lambert 1966). It is one of very few endemics in the Canadian Arctic Islands. During the summers of 1967 to 1969, Paul E. Barrett collected 182 species (WIS) on Devon Island (Barrett and Thomson 1975). During 1967, the bryologist Marian Kuc collected 21 species (CANL) from western Axel Heiberg Island at Good Friday Bay. In 1967 also, Royce Longton collected (CANL) at Van Hauen Pass on Ellesmere Island. In 1964 and 1967, the bryologist Guy Brassard collected at Tanquary Fiord, Ellesmere Island and Ward Hunt Island.

The 1970s saw continued activities in the Arctic Islands. In 1972 Stuart MacDonald collected 20 species on Hans Island, and in 1975 he collected 19 specimens on Seymour Island. In 1973, I.M. Brodo and Robert Ireland collected extensively at Polar Bear Pass on Bathurst Island, compiling a list of approximately 175 species of lichens with vouchers

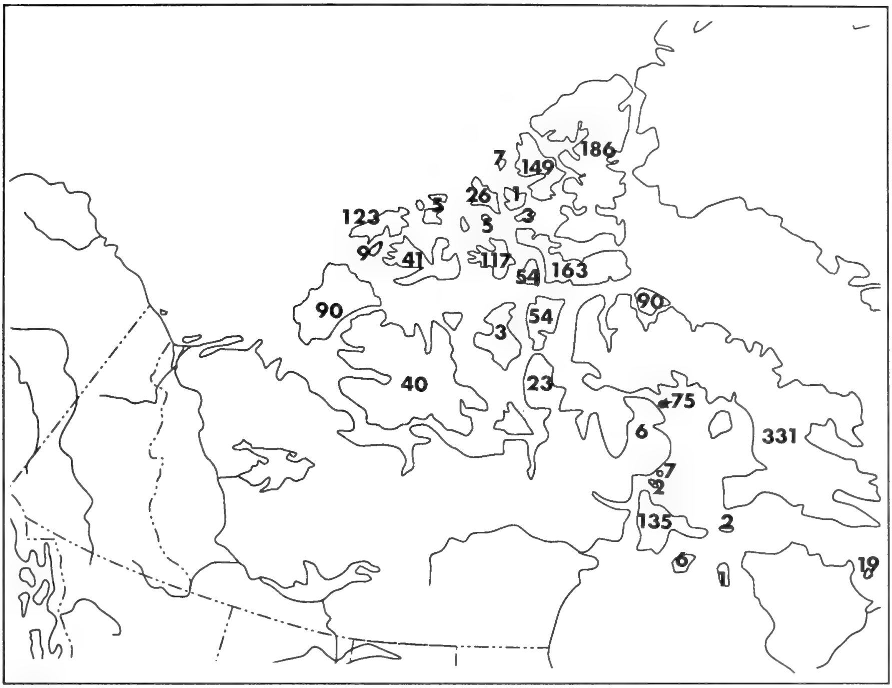

FIGURE 1: The Canadian Arctic Islands showing the number of lichen species known from each.

FIGURE 2: W.A. Weber collecting on a lichen-rich, late-snow rocky slope near Frobisher Bay (Apex), Baffin Island.

in CANL (Brodo, unpublished manuscript). In 1973 C.D. Bird (1975) collected lichens on Prince Patrick Island. He reported 123 species, 103 of them new to the island. In 1974 G. Parker collected 59 specimens at Bailey Point, Melville Island. During 1975 D.W. Wood collected specimens on Victoria Island, while H. Loney Dickson, Norton Miller, and Weston Blake collected at Polar Bear Pass, Bathurst Island. In 1976 Nancy McCartney and Allen P. McCartney studied lichens and their relationship to archaeological sites on Somerset Island, listing 54 species (McCartney 1978). George W. Scotter continued his northern studies, bringing back 179 species from eastern Axel Heiberg Island and the Fosheim Peninsula of Ellesmere Island (Thomson and Scotter 1985).

During 1981, Marjorie L.N. Nams collected 55 specimens on Ellesmere Island. In 1985 Rupert Warren and Ursula Peterson collected independently at Igloolik Island. The specimens are at TRTS and WIS respectively.

LICHEN MAPS FOR THE CANADIAN ARCTIC ISLANDS

Specimens brought back by many of the collectors have not been the subject of special reports. However, as the specimens have been deposited in herbaria such as those of the National Museum of Natural Sciences in Ottawa (CANL), the University of Wisconsin (WIS), or the Farlow Herbarium at Harvard University (FH) (and in the case of the earlier collections in various European herbaria) they became the source of data for many special papers when lichen genera were studied by specialists. I have examined the monographs in search of maps which would incorporate such information on the Arctic Islands (Table 1).

ECOLOGY

Papers specifically describing ecological conditions of lichens in the Arctic Islands are rare. Although listing few lichens, a description of communities on Cornwallis, Southampton, and Victoria islands by Leonard (1961) gives an idea of conditions there.

TABLE 1: LICHEN SPECIES FOR WHICH THERE ARE MAPS IN MONOGRAPHS SHOWING DISTRIBUTION IN THE CANADIAN ARCTIC ISLANDS[1].

Alectoria nigricans, A. ochroleuca, A. sarmentosa (Brodo and Hawksworth 1977)
Allantoparmelia almquistii, A. alpicola (Esslinger 1977)
Asahinea chrysantha (Thomson 1972)
Baeomyces carneus (Thomson 1967)
Buellia epigaea (Thomson 1972)
Bryoria chalybeiformis, B. lanestris, B. nitidula, B. tenuis (Brodo and Hawksworth 1977)
Catapyrenium cinereum, C. lachneum (Thomson 1987)
Cetraria nivalis (Thomson 1972)
Dactylina arctica, D. behringii, D. madreporiformis, D. ramulosa (Thomson and Bird 1978)
Endocarpon tortuosum (Thomson 1972)
Haematomma lapponicum (Thomson 1968)
Lecanora cenisia, L. epibryon (Brodo 1984), L. luteovernalis (Brodo 1984)
Lecidea auriculata (Hertel 1977), *L. hypocrita, L. umbonata* (Hertel 1973)
Massalongia carnosa (Henssen 1963)
Melanelia disjuncta, M. elegantula, M. exasperatula, M. stygia (Esslinger 1977)
Neuropogon sulphureus (Lynge 1940, Thomson 1972)
Pertusaria coriacea, P. dactylina, P. octomela, P. oculata, P. panyrga, P. subobducens (Dibben 1980)
Phaeophyscia sciastra (Thomson 1963)
Physcia caesia, P. dubia (Thomson 1963)
Physconia muscigena (Thomson 1963)
Placopsis gelida (Thomson 1972)
Placynthium aspratile, P. nigrum (Henssen 1963)
Pseudephebe minuscula, P. pubescens (Brodo and Hawksworth 1977)
Ramalina almquistii (Thomson 1972)
Stereocaulon arenarium (Lamb 1972)
Teloschistes arcticus (Thomson 1972)
Umbilicaria cylindrica, U. hyperborea, U. proboscidea, U. vellea (Llano 1950), *U. havaasii* (Thomson 1972)
Vestergrenopsis isidiata (Thomson 1972)

1 It should be noted that for all macrolichens, the maps are updated (see Thomson 1984).

The introduction to Schuster *et al.*, (1959) cites none of the lichens listed in the paper but gives a vivid idea of the polar-desert vegetation of northern Ellesmere Island.

In 1936 Nicholas Polunin made extensive ecological studies of those parts of the islands that he visited. They included parts of Ellesmere, Devon, Cornwallis, Somerset, Baffin, and Southampton islands, as well as Melville Peninsula and other mainland localities, and the islands of Hudson Bay. Polunin's (1948) abundant photographs give an excellent idea of the terrain and plant-cover. In some of his discussions of the communities, lichens are listed or mentioned. Although his publication was delayed until after the Second World War, it is the most comprehensive coverage to that date.

Barrett and Thomson (1975) give information on the coastal lowland of Devon Island, including communities on boulder outcrops, raised-beach crests and foreslopes, and non-sorted circles and nets. Bird (1975) discussed the vegetation on a part of Prince Patrick Island in terms of terricolous species in wet soils, frost-crack and bird-perch areas. Rocky sites were only on silicate rocks, but some were enriched by birds. Some lichens occurred on vegetation, some on old antlers and bone, and some on dung. This useful paper lists 17 site-types and provides photographs of each.

Richardson and Finegan (1977) give recent information on Devon Island, including details of lichen-cover values in the various areas studied, the communities present, the standing crop, as well as much information on lichen physiology and productivity.

LICHENOMETRY

The Canadian Arctic Islands have been the scene of studies using lichen growth-rates in measuring the rates of glacier recession and other phenomena, a science known as lichenometry. The Baffin Island Expedition of 1950 undertook studies of this type at the margin of Barnes Ice Cap. Initial studies by Hale indicated that a recession following a readvance of the southeastern lobe began about 1860 (Ward 1952). From 1961 to 1963 Andrews and Webber (1969), working near the northwestern margin of Barnes Ice Cap, critically evaluated lichenometric studies, and gave dates for the recession of that portion of the ice cap during the last 5,000 years. They also described drainage of a marginal lake about 700 A.D. Two lichens were used in these studies, *Alectoria minuscula* (*Pseudephebe*

minuscula) and *Rhizocarpon geographicum* (Andrews and Webber 1964, 1969; Andrews 1968; Ives 1962; Løken and Andrews 1966).

During 1960 and 1962 Beschel (1963) worked near Expedition Fiord on Axel Heiberg Island. He cited growth-rates for several lichens present and compared lichen thalli on moraines along the fronts of White and Iceberg glaciers.

SUMMARY

The number of lichen species thus far known from the islands is summarized (Table 2). The best known island in terms of number of species is Baffin with 331. Next is Ellesmere Island with 186, and in sequence: Devon (163), Axel Heiberg (149), Southampton (135), Prince Patrick (123), Bathurst (117) (however 175 species are in Brodo's unpublished study). From there the numbers dwindle, many islands being represented by exceedingly few collections. If an island is not listed, its lichen flora is unknown. Islands best represented are, as would be expected, those that have been visited by professional lichenologists and by outstanding collectors such as Scotter. Figure 3 shows the distribution of the numbers of species known from various islands, and species known from the islands are listed in Table 3 (follows References).

Of the 968 lichens known from the North American Arctic, so far 456 species are known from the Canadian Arctic Islands. Further exploration will improve such figures as 170 species being known from only one island so far, 71 species from two islands, 65 species from three islands, 45 species from four islands, etc. Only one species (*Ochrolechia frigida*) is known from 18 islands, one species (*Physconia muscigena*) from 15 islands, one species (*Thamnolia subuliformis*) from 14 islands, and three species (*Alectoria nigricans, Pachyospora verrucosa*, and *Rhizocarpon geographicum*) from 13 islands.

Although our knowledge of the lichen species that are present on the Arctic Islands is well advanced, it is far from complete, and much more needs to be done. Thomson (1984) merely provides a recent progress report on the status of American Arctic lichens. So many of the islands remain unstudied and the area is so vast that the opportunities are great for future investigators. In the realms of lichen ecology and physiology in the Arctic, an immense amount of work remains. We are in the pioneering stage.

FIGURE 3: High Arctic desert-like area near Resolute, Cornwallis Island. The lichens are mainly confined to the dark areas where drainage during the short spring melt period provides moisture.

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I thank I.M. Brodo for access to his unpublished preliminary paper on Bathurst Island lichens, and Pak Yau Wong for data on some collectors.

TABLE 2: LICHEN SPECIES KNOWN FROM THE CANADIAN ARCTIC ISLANDS[1].

ISLAND	MACROLICHENS	MICROLICHENS	TOTAL
Akpatok	4	15	19
Amund Ringnes	1	0	1
Axel Heiberg	60	89	149
Baffin	143	188	331
Banks	35	55	90
Bathurst	30	87	117
Boothia Peninsula	15	8	23
Borden	3	2	5
Bylot	33	57	90
Coats	4	2	6
Cornwall	1	0	1
Cornwallis	19	35	54
Devon	72	91	163
Eglinton	9	0	9
Ellef Ringnes	15	11	26
Ellesmere	67	119	186
Hans	6	15	21
Igloolik	0	9	9
Lougheed	3	2	5
Mansel	1	0	1
Meighen	7	0	7
Melville	30	11	41
Melville Peninsula	2	4	6
Nottingham	2	0	2
Prince of Wales	2	1	3
Prince Patrick	59	64	123
Seymour	13	7	20
Somerset	29	25	54
Southampton	83	52	135
Vansittart	1	1	2
Victoria	25	15	40
Winter	0	7	7

[1] Includes adjacent areas like Boothia and Melville peninsulas.

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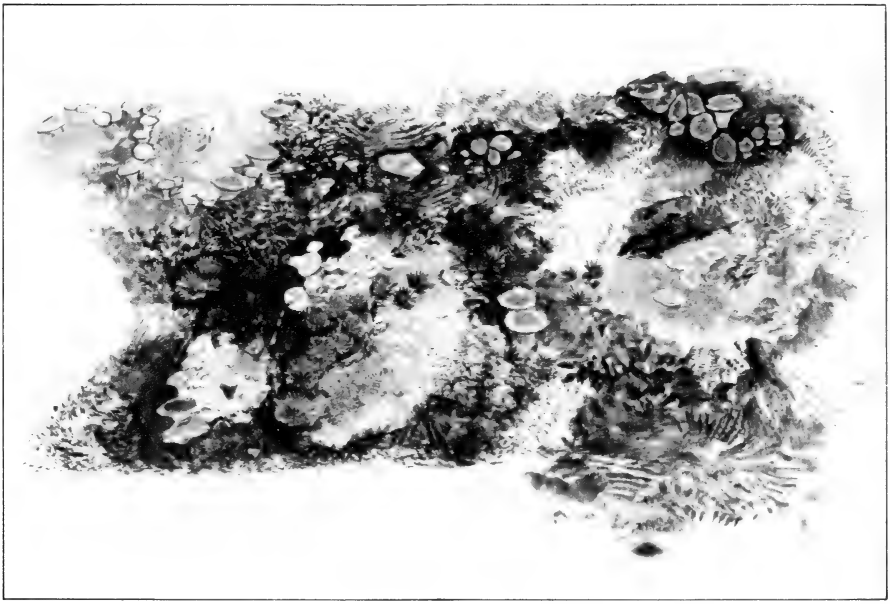

Illustrated by Brenda Carter

TABLE 3: LICHENS OF THE CANADIAN ARCTIC ISLANDS.

Acarospora badiofusca (Nyl.) Th. Fr. **Baffin, Bylot, Banks.**
Acarospora chlorophana (Wahlenb. ex Ach.) Mass. **Axel Heiberg, Baffin, Ellesmere, Prince Patrick, Somerset.**
Acarospora fuscata (Nyl.) Arn. Ach. **Axel Heiberg, Bathurst.**
Acarospora glaucocarpa (Wahlenb. in Ach.) Koerb. **Devon.**
Acarospora molybdina (Wahlenb. in Ach.) Trev. **Baffin, Ellesmere, Victoria.**
Acarospora oxytona (Ach.) Mass. **Baffin.**
Acarospora peliscypha Th. Fr. **Axel Heiberg.**
Acarospora pyrenopsoides Magn. **Ellesmere.**
Acarospora scabrida Hellb. ex Magn. **Axel Heiberg, Ellesmere.**
Acarospora sinopica (Wahlenb. ex Ach.) Koerb. **Baffin.**
Acarospora smaragdula (Wahlenb. ex Ach.) Mass. **Ellef Ringnes.**
Acarospora veronensis Mass **Axel Heiberg, Baffin.**
Agyrophora leiocarpa (DC. in Lam. & DC.) Gyel. **Somerset.**
Agyrophora *lyngei (Schol.)* Llano **Baffin, Devon, Ellesmere, Seymour, Somerset, *Victoria.***
Alectoria nigricans (Ach.) Nyl. **Axel Heiberg, Banks, Bathurst, Boothia Peninsula, Ellef Ringnes, Ellesmere, Meighen, Melville, Prince Patrick, Somerset, Southampton, Victoria.**
Alectoria ochroleuca (Hoffm.) Mass. **Axel Heiberg, Baffin, Banks, Devon, Ellef Ringnes, Ellesmere, Meighen, Melville, Melville Peninsula, Prince Patrick, Seymour.**
Alectoria vexillifera (Nyl.) Stiz. **Baffin, Ellesmere, Southampton.**
Allantoparmelia almquistii (Vainio) Essl. **Baffin.**
Allantoparmelia alpicola (Th. Fr.) Essl. **Baffin, Bathurst, Ellesmere, Southampton.**
Amygdalaria pelobotryon (Wahlenb. in Ach.) Norm. **Baffin.**
Anaptychia setifera Raes. (= *A kaspica*) **Akpatok.**
Arctomia delicatula Th. Fr. **Baffin, Ellesmere.**
Arctoparmelia centrifuga (L.) Hale **Baffin, Boothia Peninsula.**
Arctoparmelia incurva (Pers.) Hale **Baffin, Devon, Southampton.**
Arctoparmelia separata (Th. Fr.) Hale **Axel Heiberg, Baffin, Banks, Devon, Ellesmere, Melville, Melville Peninsula, Prince Patrick, Southampton, Victoria.**
Arthrorhaphis alpina (Schaer.) R. Sant. **Baffin, Prince Patrick.**
Asahinea chrysantha (Tuck.) W. Culb. & C. Culb. **Baffin.**
Aspicilia alboradiata (Magn.) Oxner **Ellesmere.**
Aspicilia alphoplaca (Wahlenb. in Ach.) Poelt & Leuckert **Baffin.**
Aspicilia anseris (Lynge) Thoms. **Axel Heiberg, Baffin, Ellesmere, Igloolik.**
Aspicilia arctica (Lynge) Oxner **Axel Heiberg.**
Aspicilia caesiocinerea (Nyl. ex Malbr.) Arn. **Akpatok.**

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TABLE 3: (cont'd)

Aspicilia candida (Anzi) Hue **Baffin, Banks, Bathurst, Bylot, Cornwallis, Ellesmere.**
Aspicilia cingulata (Zahlbr.) Oxner **Axel Heiberg, Baffin, Ellesmere.**
Aspicilia composita (Lynge) Thoms. **Axel Heiberg, Baffin, Ellesmere.**
Aspicilia contigua (Lynge) Thoms. **Axel Heiberg.**
Aspicilia disserpens (Zahlbr.) Raes. in Huusk. **Baffin, Bylot, Ellesmere, Igloolik, Prince Patrick, Southampton.**
Aspicilia fimbriata (Magn.) Clauz. & Rondon **Baffin.**
Aspicilia lesleyana Darb. **Axel Heiberg, Devon, Ellesmere.**
Aspicilia melanaspis (Ach.) Poelt & Leuckert **Baffin.**
Aspicilia morioides Blomb. ex. Arn. **Baffin, Bylot.**
Aspicilia myrini (Fr. in Myrin) B. Stein **Baffin.**
Aspicilia nathorstii (Lynge) Thoms. **Ellesmere.**
Aspicilia perradiata (Nyl.) Hue **Axel Heiberg, Baffin, Bathurst, Bylot, Ellesmere, Prince Patrick, Southampton.**
Aspicilia pertusa (Lynge) Thoms. **Baffin, Devon.**
Aspicilia plicigera (Zahlbr.) Raes. **Axel Heiberg, Bylot.**
Aspicilia rosulata Koerb. **Baffin, Banks, Bathurst, Bylot, Ellesmere.**
Aspicilia subplicigera (Magn.) Oxner **Cornwallis.**
Aspicilia subradians (Nyl.) Hue **Baffin.**
Aspicilia supertegens Arn. **Baffin, Ellesmere.**
Bacidia bagliettoana (Mass. & DeNot. in Mass.) Jatta **Baffin, Devon, Southampton.**
Bacidia sabuletorum (Schreb.) Lett. (*Mycobilimbia sabuletorum* (Schreb.) Hafellner) **Baffin.**
Bacidia verecundula (Th. Fr.) Magn. **Ellesmere.**
Baeomyces carneus Floerke **Baffin, Ellesmere.**
Baeomyces placophyllus Ach. **Baffin.**
Bellemerea alpina (Sommerf.) Clauz & Roux **Ellesmere.**
Bellemerea cinereorufescens (Ach.) Clauz. & Roux **Banks.**
Brigantiaea fuscolutea (Dicks.) R. Sant. **Baffin, Ellesmere, Igloolik.**
Brodoa oroarctica (Krog) Goward **Baffin, Ellesmere, Southampton.**
Bryocaulon divergens (Ach.) Kaernef. **Axel Heiberg, Baffin, Banks, Devon, Ellesmere, Southampton.**
Bryonora castanea (Hepp) Poelt **Baffin, Devon.**
Bryonora curvescens (Mudd) Poelt **Devon.**
Bryoria chalybeiformis (L.) Brodo & Hawksw. **Baffin, Banks, Devon, Ellesmere, Melville, Prince Patrick, Southampton.**

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TABLE 3: (cont'd)

Bryoria nitidula (Th. Fr.) Brodo & Hawksw. **Axel Heiberg, Baffin, Bathurst, Devon, Ellesmere, Melville, Prince Patrick, Southampton.**
Buellia aethalea (Ach.) Th. Fr. **Baffin, Ellesmere.**
Buellia alboatra (Hoffm.) Th. Fr. **Ellesmere, Prince Patrick, Victoria.**
Buellia elegans Poelt Ellesmere.
Buellia erubescens Arn. *(B. zahlbruckneri)* **Banks.**
Buellia geophila (Floerke ex Sommerf.) Lynge **Baffin, Bylot, Devon, Ellesmere.**
Buellia leptocline (Flot.) Mass. **Axel Heiberg, Devon.**
Buellia nivalis (Bagl. & Carest) Hertel **Axel Heiberg, Banks, Devon, Prince Patrick.**
Buellia papillata (Sommerf.) Tuck. **Axel Heiberg, Baffin, Banks, Bathurst, Bylot, Cornwallis, Devon, Lougheed, Melville, Prince Patrick, Southampton.**
Buellia pulverulenta (Anzi) Jatta **Banks, Bylot.**
Buellia punctata (Hoffm.) Mass. **Baffin, Bylot, Southampton.**
Buellia spuria (Schaer.) Anzi **Prince Patrick.**
Buellia stigmatea (Ach.) Koerb. **Axel Heiberg.**
Buellia vilis Th. Fr. **Ellesmere**
Caloplaca alcarum Poelt **Axel Heiberg.**
Caloplaca celata Th. Fr. **Banks, Ellesmere.**
Caloplaca cinnamomea (Th. Fr.) Oliv. **Baffin, Ellesmere, Prince Patrick, Southampton.**
Caloplaca cirrochroa (Ach.) Th. Fr. **Baffin, Ellesmere.**
Caloplaca citrina (Hoffm.) Th. Fr. **Bathurst, Ellesmere.**
Caloplaca crenularia (With.) Laund (*C. festiva*) **Axel Heiberg, Baffin, Banks, Bylot, Ellef Ringnes, Southampton.**
Caloplaca *exsecuta (Nyl.)* Dalla Torre & Sarnth. **Bathurst, Melville, Prince Patrick.**
Caloplaca fraudans (Th. Fr.) Oliv. **Baffin.**
Caloplaca friesii Magn. **"South Borden"**[1].
Caloplaca holocarpa (Hoffm.) Wade **Baffin, Banks, Bathurst, Devon, Prince Patrick.**
Caloplaca invadens Lynge **Baffin, Ellesmere.**
Caloplaca jungermanniae (Vahl) Th. Fr. **Axel Heiberg, Baffin, Banks, Bathurst, Devon, Prince Patrick, Southampton.**
Caloplaca saxicola (Hoffm.) Nordin **Baffin, Southampton.**
Caloplaca stillicidiorum (Vahl) Lynge **Axel Heiberg, Baffin, Banks, Boothia Peninsula, Cornwallis, Ellesmere, Prince Patrick, Somerset, Southampton.**
Caloplaca tetraspora (Nyl.) Oliv. **Axel Heiberg, Baffin, Bathurst, Bylot, Devon, Ellesmere, Southampton.**

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[1] Ed. note: Presumably this refers to Mackenzie King Island, once thought to be the southern part of Borden Island.

TABLE 3: (cont'd)

Caloplaca tiroliensis Zahlbr. **Axel Heiberg, Baffin, Banks, Bathurst, Boothia Peninsula, Bylot, Devon, Ellesmere, Prince Patrick, Somerset, Southampton.**

Caloplaca tominii Savicz **Ellesmere.**

Caloplaca tornoensis Magn. **Baffin.**

Candelariella arctica (Koerb.) R. Sant. **Bylot, Devon.**

Candelariella aurella (Hoffm.) Zahlbr. **Axel Heiberg, Baffin, Banks, Bathurst, Bylot, Cornwallis, Devon, Ellesmere.**

Candelariella dispersa (Raes.) Hakul. **Bathurst, Ellesmere.**

Candelariella placodizans (Nyl.) Magn. **Baffin, Bylot.**

Candelariella terrigena Raes. **Baffin, Banks, Bathurst, Boothia Peninsula, Devon, Ellesmere, Prince Patrick.**

Candelariella vitellina (Hoffm.) Muell. Arg. **Baffin, Bylot.**

Candelariella xanthostigma (Ach.) Lettau **Southampton.**

Carbonea vitellinaria (Nyl.) Hertel **Ellesmere.**

Carbonea vorticosa (Floerke) Hertel **Axel Heiberg, Baffin, Banks, Ellesmere.**

Catapyrenium cinereum (Pers.) Koerb. **Southampton.**

Catapyrenium lachneum (Ach.) R. Sant. **Baffin, Cornwallis.**

Catillaria athallina (Hepp) Hellb. **Cornwallis.**

Catillaria chalybeia (Borrer) Mass. **Baffin.**

Cephalophysis leucospila (Anzi) Kilias & Schneid. **Baffin, Cornwallis, Ellesmere.**

Cetraria andrejevii Oxner **Baffin, Eglinton, Southampton.**

Cetraria commixta (Nyl.) Th. Fr. **Axel Heiberg, Baffin.**

Cetraria cucullata (Bell.) Ach. **Baffin, Banks, Bylot, Cornwallis, Ellesmere, Melville, Prince Patrick, Somerset, Southampton, Victoria.**

Cetraria delisei (Bory ex Schaer.) Nyl. **Akpatok, Baffin, Banks, Bathurst, Bylot, Devon, Ellef Ringnes, Melville, Prince Patrick, Seymour, Southampton, Victoria.**

Cetraria ericetorum Opiz **Baffin, Banks, Boothia Peninsula, Devon, Ellesmere, Seymour, Southampton.**

Cetraria fastigiata (Del. ex Nyl. in Norrl.) Karnef. **Baffin, Borden, Eglinton, Ellef Ringnes, Melville, Prince Patrick, Southampton.**

Cetraria hepatizon (Ach.) Vainio **Baffin, Ellesmere, Prince Patrick, Southampton.**

Cetraria islandica (L.) Ach. **Akpatok, Axel Heiberg, Baffin, Banks, Devon, Ellesmere, Prince Patrick, Southampton.**

Cetraria laevigata Rass. **Axel Heiberg, Banks, Eglinton, Meighen, Melville, Prince Patrick, Somerset.**

Cetraria nigricans Nyl. **Baffin, Ellesmere.**

Cetraria nigricascens (Nyl. in Kihlm.) Elenk. **Axel Heiberg, Baffin, Eglinton, Lougheed, Melville, Prince Patrick, Somerset.**

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TABLE 3: (cont'd)

Certraria nivalis (L.) Ach. **Akpatok, Axel Heiberg, Baffin, Banks, Coats, Devon, Eglinton, Ellesmere, Melville, Prince Patrick, Seymour, Somerset, Southampton.**

Cetraria tilesii Ach. **Baffin, Banks, Boothia Peninsula, Devon, Ellesmere, Melville, Prince of Wales, Prince Patrick, Somerset, Southampton, Victoria.**

Cladina aberrans (Abb.) Hale & W. Culb. **Baffin.**

Cladina mitis (Sandst.) Hustich **Axel Heiberg, Baffin, Banks, Devon.**

Cladina rangiferina (L.) Nyl. **Baffin, Southampton.**

Cladina stellaris (Opiz) Brodo **Baffin.**

Cladonia amaurocraea (Floerke) Schaer. **Axel Heiberg, Baffin, Boothia Peninsula, Bylot, Devon, Prince Patrick, Southampton.**

Cladonia bellidiflora (Ach.) Schaer. **Baffin, Devon, Seymour.**

Cladonia cariosa (Ach.) Spreng. **Baffin.**

Cladonia carneola (Fr.) Fr. **Southampton.**

Cladonia chlorophaea (Floerke ex Sommerf.) Spreng. **Axel Heiberg, Bylot, Coats, Ellesmere.**

Cladonia coccifera (L.) Willd. **Axel Heiberg, Baffin, Coats, Devon, Ellesmere, Southampton.**

Cladonia cornuta (L.) Hoffm. **Baffin, Southampton.**

Cladonia cyanipes (Sommerf.) Nyl. **Baffin.**

Cladonia deformis (L.) Hoffm. **Baffin, Southampton.**

Cladonia ecmocyna Leight. **Axel Heiberg, Banks, Eglinton.**

Cladonia fimbriata (L.) Fr. **Baffin, Southampton.**

Cladonia gracilis (L.) Willd. var. gracilis **Baffin, Devon, Melville, Southampton.**

Cladonia macrophylla (Schaer.) Stenham **Baffin, Southampton.**

Cladonia macrophyllodes Nyl. **Southampton.**

Cladonia pleurota (Floerke) Schaer. **Axel Heiberg, Baffin, Prince Patrick.**

Cladonia pocillum (Ach.) O. Rich. **Axel Heiberg, Baffin, Banks, Bathurst, Boothia Peninsula, Devon, Ellesmere, Prince Patrick, Somerset, Southampton, Victoria.**

Cladonia pyxidata (L.) Hoffm. **Axel Heiberg, Baffin, Banks, Cornwallis, Ellesmere, Prince Patrick, Southampton, Victoria.**

Cladonia stricta (Nyl.) Nyl. **Baffin, Banks, Southampton.**

Cladonia subcervicornis (Vainio) Kernst. **Baffin, Devon, Prince Patrick.**

Cladonia subfurcata (Nyl.) Arn. **Baffin.**

Cladonia uncialis (L.) Weber ex Wigg. **Axel Heiberg, Baffin, Banks, Southampton.**

Coelocaulon aculeatum (Schreb.) Link. **Baffin, Banks, Bathurst, Cornwallis, Devon, Ellesmere, Somerset, Southampton, Victoria.**

Coelocaulon muricatum (Ach.) Laundon **Baffin, Devon.**

Collema ceraniscum Nyl. **Baffin, Bathurst, Devon, Ellesmere, Southampton.**

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TABLE 3: (cont'd)

Collema fuscovirens (With.) Laund. *(C. tuniforme)* **Ellesmere.**
Collema glebulentum (Nyl. ex Cromb.) Degel. **Baffin.**
Collema tenax (Sw.) Ach. **Baffin, Banks, Cornwallis, Ellesmere, Melville.**
Collema undulatum Laur. ex Flot. **Bathurst, Devon, Ellesmere.**
Coriscium viride (Ach.) Vainio **Baffin.**
Cornicularia divergens Ach. **Axel Heiberg, Baffin, Banks, Devon, Ellesmere, Southampton.**
Dactylina arctica (Richards.) Nyl. **Axel Heiberg, Baffin, Banks, Boothia Peninsula, Eglinton, Melville, Prince Patrick, Somerset, Southampton.**
Dactylina beringica Thoms. & Bird **Baffin, Banks, Devon.**
Dactylina madreporiformis (Ach.) Tuck. **Banks, Bathurst, Bylot, Victoria.**
Dactylina ramulosa (Hook.) Tuck. **Axel Heiberg, Baffin, Banks, Bathurst, Boothia Peninsula, Cornwallis, Devon, Ellesmere, Meighen, Melville, Prince Patrick, Somerset, Southampton.**
Dermatocarpon intestiniforme (Koerb.) Hasse **Devon.**
Dimelaena oreina (Ach.) Norm. **Baffin, Bylot.**
Diploschistes muscorum (Scop.) R.Sant. **Baffin.**
Diploschistes scruposus (Schreb.) Norm. **Baffin, Banks.**
Eiglera flavida (Hepp) Hafellner **Baffin, Bathurst, Ellesmere.**
Endocarpon tortuosum Herre **Baffin.**
Ephebe lanata (L.) Vain. **Baffin.**
Epilichen scabrosus (Ach.) Clem. ex Hafellner **Baffin.**
Evernia perfragilis Llano **Baffin, Banks, Bathurst, Cornwallis, Somerset, Victoria.**
Farnoldia jurana (Schaer.) Hertel **Baffin, Banks, Bathurst.**
Fistulariella almquistii (Vainio) Bowler & Rundel **Boothia Peninsula, Somerset.**
Fulgensia bracteata (Hoffm.) Raes. **Axel Heiberg, Baffin, Banks, Bathurst, Cornwallis, Devon, Melville, Somerset, Southampton.**
Fuscidea mollis (Wahlenb.) V. Wirth & Vezda **Baffin.**
Glypholecia scabra (Pers.) Muell. Arg. **Axel Heiberg.**
Gyalecta foveolaris (Ach.) Schaer. **Banks, Cornwallis, Devon.**
Gyalecta geoica (Wahlenb. ex Ach.) Ach. **Baffin.**
Gyalecta peziza (Mont.) Anzi **Devon, Ellesmere.**
Haematomma lapponicum Raes. **Baffin, Bathurst, Bylot, Devon, Ellesmere, Seymour, Southampton.**
Hymenelia lacustris (Wityh.) Poelt & Vezda **Baffin.**
Hypogymnia austerodes (Nyl.) Raes. **Baffin, Ellesmere, Melville, Southampton.**
Hypogymnia physodes (L.) Nyl. **Baffin, Devon, Southampton.**

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TABLE 3: (cont'd)

Hypogymnia subobscura (Vainio) Poelt **Baffin, Banks, Bathurst, Boothia Peninsula, Ellesmere, Prince Patrick, Seymour, Somerset, Southampton.**
Ionaspis epulotica (Ach.) Blomb. & Forss. **Baffin, Bathurst, Devon, Ellesmere.**
Ionaspis melanocarpa (Kremph.) Arn. **Baffin, Bathurst, Devon, Southampton, Victoria.**
Ionaspis schismatopsis (Nyl.) Hue **Axel Heiberg, Baffin, Banks, Bathurst, Cornwallis.**
Lecania alpivaga Th. Fr. **Baffin, Devon.**
Lecania thallophila Magn. **Bathurst.**
Lecania allophana Nyl. **Southampton.**
Lecanora argopholis (Ach.) Ach. **Baffin, Devon, Prince Patrick.**
Lecanora atrosulphurea (Wahlenb.) Ach. **Axel Heiberg, Baffin, Cornwallis, Devon, Ellef Ringnes, Ellesmere.**
Lecanora beringii Nyl. **Baffin, Bathurst, Bylot, Devon, Prince Patrick.**
Lecanora cenisia Ach. **Axel Heiberg, Baffin, Ellesmere, Prince Patrick, Southampton.**
Lecanora circumborealis Brodo & Vitik. **Baffin.**
Lecanora congesta Lynge **Axel Heiberg.**
Lecanora crenulata Hook. **Axel Heiberg, Bathurst.**
Lecanora dispersa (Pers.) Sommerf. **Axel Heiberg, Baffin, Banks, Bathurst, Cornwallis, Devon, Ellesmere, Prince Patrick.**
Lecanora epibryon (Ach.) Ach. **Axel Heiberg, Baffin, Banks, Bathurst, Bylot, Cornwallis, Devon, Ellesmere, Southampton.**
Lecanora geophila (Th. Fr.) Poelt **Axel Heiberg, Baffin, Prince Patrick.**
Lecanora groenlandica Lynge **Axel Heiberg, Ellesmere.**
Lecanora intricata (Ach.) Ach. **Baffin, Bylot, Devon.**
Lecanora luteovernalis Brodo **Banks, Bathurst, Cornwallis, Devon, Ellesmere, Southampton, Victoria.**
Lecanora marginata Schaer. **Axel Heiberg, Baffin, Banks, Bathurst, Bylot, Cornwallis, Ellef Rignes, Somerset, Southampton.**
Lecanora maxima Lynge **Baffin.**
Lecanora microfusca Lynge **Baffin.**
Lecanora nordenskioeldii Vainio **Baffin, Devon, Somerset.**
Lecanora polytropa (Hoffm.) Rabenh. **Axel Heiberg, Baffin, Banks, Bathurst, Bylot, Devon, Prince Patrick, Southampton.**
Lecanora rupicola (L.) Zahlbr. **Akpatok, Axel Heiberg, Baffin, Banks, Devon, Igloolik, Prince Patrick, Southampton.**
Lecanora torrida Vainio **Baffin, Bathurst, Bylot, Ellesmere.**
Lecanora zosterae (Ach.) Nyl. **Axel Heiberg, Banks, Bathurst, Ellesmere.**

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TABLE 3: (cont'd)

Lecidea alpestris Sommerf. **Baffin.**
Lecidea atrobrunnea (Ram. in Lam. & DC.) Schaer. **Baffin, Bathurst, Devon.**
Lecidea auriculata Th. Fr. **Axel Heiberg, Baffin, Banks, Bathurst, Ellesmere, Prince Patrick, Southampton.**
Lecidea berengeriana (Mass.) Th. Fr. **Baffin, Southampton.**
Lecidea circumnigrata Magn. in Degel. **Axel Heiberg, Bathurst, Ellesmere, Prince Patrick.**
Lecidea confluens (G. Web.) Ach. **Axel Heiberg, Baffin, Cornwallis, Ellesmere.**
Lecidea cuprea Sommerf. **Axel Heiberg, Baffin, Ellef Ringnes, Melville, Southampton.**
Lecidea diapensiae Th. Fr. **Baffin.**
Lecidea diducens Nyl. **Ellesmere.**
Lecidea ecrustacea (Anzi ex Arn.) Arn. **Baffin.**
Lecidea ementiens Nyl. **Baffin, Ellesmere.**
Lecidea garovaglii Schaer. **Baffin.**
Lecidea hypocrita Mass. **Banks, Bathurst, Cornwallis, Devon, Southampton.**
Lecidea impavida Th. Fr. **Vansittart.**
Lecidea lactea Floerke ex Schaer. (incl. *L. cyanescens* Lynge) **Baffin, Banks, Bathurst.**
Lecidea lapicida (Ach.) Ach. **Axel Heiberg, Baffin, Banks, Bathurst, Devon, Ellesmere, Melville, Prince Patrick, Somerset.**
Lecidea leptoboloides Nyl. **Ellesmere.**
Lecidea leucophaea (Floerke ex Rabenh.) Nyl. **Ellesmere.**
Lecidea limosa Ach. **Axel Heiberg, Devon, Ellesmere, Somerset, Winter.**
Lecidea lithophila (Ach.) Ach. **Akpatok.**
Lecidea lulensis (Hellb.) Stiz. **Axel Heiberg, Baffin, Devon, Ellesmere, Melville, Winter.**
Licidea occidentalis Lynge **Ellesmere.**
Lecidea paupercula Th. Fr. **Ellesmere.**
Lecidea picea Lynge **Axel Heiberg, Baffin, Bylot, Ellesmere.**
Lecidea plana (Lahm. in Koerb.) Nyl. **Ellef Ringnes.**
Lecidea promiscens Nyl. **Southampton.**
Lecidea ramulosa Th. Fr. **Axel Heiberg, Baffin, Banks, Bathurst, Bylot, Coats, Devon, Melville, Seymour, Southampton.**
Lecidea scrobiculata (Th. Fr.) Th. Fr. **Ellesmere.**
Lecidea steineri Hertel **Bathurst, Cornwallis.**
Lecidea sublimosa Nyl. **Ellesmere.**
Lecidea subrhagadiella Lynge. **Baffin.**
Lecidea tenuissima Lynge **Axel Heiberg.**

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TABLE 3: (cont'd)

Lecidea tessellata (Ach.) Floerke **Axel Heiberg, Baffin, Banks, Bathurst, Cornwallis, Ellesmere.**
Lecidea tornoensis Nyl. **Ellesmere, Prince Patrick.**
Lecidea umbonata (Hepp) Mudd **Axel Heiberg, Baffin, Ellesmere.**
Lecidea vernalis (L.) Ach. **Akpatok, Baffin, Devon, Ellesmere.**
Lecidella bullata Koerb. **Axel Heiberg, Ellesmere.**
Lecidella carpathica Koerb. **Prince Patrick.**
Lecidella euphorea (Floerke) Hertel. **Baffin, Bathurst, Southampton.**
Lecidella inamoena (Muell. Arg.) Hertel **Baffin, Bathurst, Bylot, Devon, Ellesmere, Igloolik, Melville, Victoria.**
Lecidella spitzbergensis (Lynge) Hertel & Leuck. **Axel Heiberg, Bathurst, Ellesmere.**
Lecidella stigmatea (Ach.) Hertel & Leuck. **Axel Heiberg, Baffin, Banks, Bathurst, Cornwallis, Devon, Ellesmere, Prince Patrick, Somerset.**
Lecidella wulfenii (Hepp) Koerb. **Axel Heiberg, Baffin, Bathurst, Boothia Peninsula, Devon, Ellesmere, Seymour, Southampton.**
Lecidoma demissum (Rotstr.) G. Schneid. & Hertel **Baffin.**
Leciophysma finmarkicum Th. Fr. **Axel Heiberg, Baffin, Devon.**
Leptogium arcticum P. Jorg. **Ellesmere.**
Leptogium lichenoides (L.) Zahlbr. **Baffin, Ellesmere, Southampton, Victoria.**
Leptogium minutissimum (Floerke) Fr. **Baffin, Bathurst, Devon.**
Leptogium saturninum (Dickson) Nyl. **Baffin, Prince Patrick.**
Lopadium coralloides (Nyl.) Lynge **Baffin, Southampton.**
Lopadium pezizoideum (Ach.) Koerb. **Baffin, Bathurst, Bylot, Devon, Ellesmere.**
Massalongia carnosa (Dickson) Koerb. **Baffin, Devon, Southampton.**
Melanelia exasperatula (Nyl.) Essl. **Baffin, Ellesmere.**
Melenalia incolorata (Parr.) Essl. *(M. elegantula)* **Baffin, Devon, Ellesmere, Prince Patrick, Southampton.**
Melanelia infumata (Nyl.) Essl. **Axel Heiberg, Baffin, Devon, Ellesmere, Prince Patrick, Southampton.**
Melanelia sorediata (Ach.) Goward & Ahti **Baffin.**
Melanelia stygia (L.) Essl. **Baffin, Devon, Ellesmere, Southampton, Victoria.**
Micarea assimilata (Nyl.) Coppins **Axel Heiberg, Bathurst, Bylot, Cornwallis, Devon, Prince Patrick, Somerset, Southampton.**
Micarea crassipes (Th. Fr.) Coppins *(Helocarpon crassipes* Th. Fr.) **Devon, Ellesmere.**
Micarea incrassata Hedl. **Axel Heiberg, Southampton.**
Micarea lignaria (Ach.) Hedl. **Southampton.**
Mycoblastis affinis (Schaer.) Schauer. **Baffin.**

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TABLE 3: (cont'd)

Mycoblastis sanguinarius (L.) Norm. **Baffin.**
Nephroma arcticum (L.) Torss. **Baffin.**
Nephroma expallidum (Nyl.) Nyl. **Baffin, Bylot, Devon.**
Ochrolechia androgyna (Hoffm.) Arn. **Baffin, Bylot, Devon, Southampton.**
Ochrolechia frigida (Swartz) Lynge **Akpatok, Axel Heiberg, Baffin, Banks, Bathurst, Borden, Bylot, Coats, Cornwallis, Devon, Ellesmere, Melville, Melville Peninsula, Prince Patrick, Seymour, Somerset, Southampton, Victoria.**
Ochrolechia grimmiae Lynge **Baffin, Bylot.**
Ochrolechia gyalectina (Nyl.) Zahlbr. **Baffin, Banks, Devon, Ellesmere.**
Ochrolechia inaequatula (Nyl.) Zahlbr. **Baffin, Bathurst, Devon, Seymour.**
Ochrolechia upsaliensis (L.) Mass. **Axel Heiberg, Baffin, Banks, Bathurst, Devon, Southampton.**
Omphalodiscus decussatus (Vill.) Schol. **Axel Heiberg, Baffin, Cornwallis, Ellesmere, Nottingham, Prince Patrick, Somerset, Southampton, Victoria.**
Omphalodiscus krascheninnikovii (Savicz) Schol. **Ellesmere.**
Omphalodiscus virginis (Schaer.) Schol. **Axel Heiberg, Baffin, Banks, Ellef Ringnes, Ellesmere, Somerset, Southampton.**
Orphniospora moriopsis (Mass.) Hawksw. **Baffin, Bylot, Devon, Ellesmere, Somerset.**
Pannaria hookeri (Borrer ex Sm.) Nyl. **Baffin, Devon, Ellef Ringnes.**
Pannaria pezizoides (G. Web.) Trev. **Baffin, Cornwallis, Southampton.**
Pannaria praetermissa Nyl. in Chyd. & Furuhj. **Baffin, Devon.**
Parmelia fraudans Nyl. **Devon, Southampton.**
Parmelia omphalodes (L.) Ach. **Seymour.**
Parmelia saxatilis (L.) Ach. **Baffin, Devon, Igloolik, Southampton.**
Parmelia sulcata Tayl. **Baffin, Devon, Southampton, Victoria.**
Parmeliella tryptophylla (Ach.) Muell. Arg. **Baffin.**
Peltigera aphthosa (L.) Willd. **Axel Heiberg, Baffin, Banks, Bathurst, Boothia Peninsula, Devon, Eglinton, Ellesmere, Melville, Prince Patrick, Somerset, Southampton.**
Peltigera canina (L.) Willd. **Axel Heiberg, Baffin, Banks, Devon, Southampton.**
Peltigera lepidophora (Nyl. ex Vainio) Bitt. **Baffin, Southampton.**
Peltigera leucophlebia (Nyl.) Gyel. **Baffin, Devon, Ellesmere.**
Peltigera malacea (Ach.) Funk. **Axel Heiberg, Baffin, Bathurst, Devon, Lougheed.**
Peltigera polydactyla (Neck.) Hoffm. **Baffin.**
Peltigera rufescens (Weis.) Humb. **Baffin, Bathurst, Cornwallis, Devon, Ellesmere, Mansel, Melville, Southampton.**
Peltigera scabrosa Th. Fr. **Baffin, Bathurst, Devon.**
Peltigera venosa (L.) Hoffm. **Baffin, Banks.**

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TABLE 3: (cont'd)

Pertusaria alaskensis Erichs. **Devon.**
Pertusaria bryontha (Ach.) Nyl. **Baffin, Bathurst, Devon.**
Pertusaria bryophaga Erichs. **Bathurst.**
Pertusaria coriacea (Th. Fr.) Th. Fr. **Axel Heiberg, Baffin, Bathurst, Bylot, Devon, Ellesmere, Southampton.**
Pertusaria dactylina (Ach.) Nyl. **Axel Heiberg, Baffin, Bathurst, Bylot, Devon, Ellef Ringnes, Ellesmere, Lougheed, Prince Patrick, Seymour, Southampton.**
Pertusaria geminipara (Th. Fr.) Knight **Devon, Prince Patrick.**
Pertusaria glomerata (Ach.) Schaer. **Devon.**
Pertusaria octomela (Norm.) Erichs. **Baffin, Devon.**
Pertusaria oculata (Dicks.) Th. Fr. **Akpatok, Baffin, Bylot, Igloolik.**
Pertusaria panyrga (Ach.) Mass. **Axel Heiberg, Baffin, Bathurst, Cornwallis, Devon, Ellesmere, Melville Peninsula, Southampton.**
Pertusaria pruinifera Erichs. **Devon.**
Pertusaria subobducens Nyl. **Baffin, Bathurst, Bylot, Somerset, Southampton.**
Pertusaria subplicans Nyl. **Ellesmere.**
Pertusaria trochiscea Norman **Baffin, Devon, Prince Patrick.**
Phaeophyscia constipata (Norrl. & Nyl.) Moberg **Axel Heiberg, Baffin, Devon.**
Phaeophyscia endococcinea (Koerb.) Moberg **Baffin, Bathurst.**
Phaeophyscia sciastra (Ach.) Moberg **Baffin, Bathurst, Devon, Ellef Ringnes, Somerset, Southampton.**
Phaeorrhiza nimbosa (Fr.) Mayrh. & Poelt **Axel Heiberg, Baffin, Banks, Bathurst, Boothia Peninsula, Devon, Ellesmere, Somerset, Winter.**
Phaeorrhiza sareptana (Tomin) Mayrh. & Poelt **Baffin.**
Physcia adscendens (Th. Fr.) Oliv. **Southampton.**
Physcia caesia (Hoffm.) Furnrohr. **Baffin, Banks, Bathurst, Cornwallis, Devon, Ellesmere, Somerset, Southampton.**
Physcia dubia (Hoffm.) Lettau **Baffin, Banks, Cornwallis, Devon, Ellesmere, Somerset, Southampton.**
Physconia muscigena (Ach.) Poelt **Axel Heiberg, Baffin, Banks, Boothia Peninsula, Cornwallis, Devon, Ellesmere, Meighen, Melville, Prince Patrick, Seymour, Somerset, Southampton, Victoria.**
Phytoconis viridis (Ach.) Redh. in Kuyper *(Coriscium viride)* **Baffin.**
Placopsis gelida (L.) Linds. **Baffin, Boothia Peninsula, Devon.**
Placynthiella uliginosa (Schrad.) Coppins & P. James Prince Patrick.
Placynthium aspratile (Ach.) Henss. **Baffin, Bylot, Devon, Ellesmere, Southampton.**
Placynthium nigrum (Huds.) S. Gray **Bathurst, Cornwallis, Devon, Ellesmere, Victoria.**
Platismatia glauca (L.) W. Culb. & C. Culb. **Baffin.**

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TABLE 3: (cont'd)

Polyblastia bryophila Lonnr. **Baffin, Bathurst, Devon, Ellesmere, Victoria.**
Polyblastia cruenta (Koerb.) P. James & Swinscow **Ellesmere.**
Polyblastia cupularis Mass. **Akpatopk, Ellesmere.**
Polyblastia gelatinosa (Ach.) Th. Fr. **Baffin, Bathurst, Devon.**
Polyblastia hyperborea Th. Fr. **Baffin, Bathurst, Cornwallis, Devon, Ellesmere, Igloolik, Southampton.**
Polyblastia sendtneri Kremph. **Baffin, Bathurst, Somerset.**
Polyblastia terrestris Th. Fr. **Bathurst.**
Polyblastia theleodes (Somerf.) Th. Fr. **Baffin, Bathurst, Cornwallis, Devon, Ellesmere, Prince Patrick.**
Polychidium muscicola (Sw.) S. Gray **Baffin.**
Polysporina simplex (Davies) Vezda **Axel Heiberg, Baffin, Bylot, Ellesmere, Somerset.**
Porpidia crustulata (Ach.) Hertel & Knoph **Baffin.**
Porpidia flavocaerulescens (Hornem) Hertel & Schwab. **Baffin, Devon.**
Porpidia glaucophaea (Koerb.) Hertel & Knoph **Axel Heiberg, Baffin, Bathurst, Devon.**
Porpidia macrocarpa (DC. in Lam. & DC.) Hertel & Schwab **Baffin, Devon, Prince Patrick.**
Porpidia speirea (Ach.) Krempelh. **Baffin, Banks, Devon, Melville Peninsula.**
Protoblastenia calva (Dickson) Zahlbr. **Akpatok, Baffin, Bathurst, Devon.**
Protoblastenia rupestris (Scop.) Stein. **Baffin, Cornwallis, Ellesmere, Southampton.**
Protoblastenia terricola (Anzi) Lynge **Bathurst, Cornwallis, Ellesmere.**
Protoparmelia badia (Hoffm.) Hafellner **Baffin, Banks, Bathurst, Bylot, Cornwallis, Ellef Ringnes.**
Protothelenella corrosa (Koerb.) Mayrh. & Poelt. **Ellesmere.**
Pseudephebe minuscula (Nyl. ex. Arn.) Brodo & Hawksw. **Axel Heiberg, Baffin, Devon, Ellesmere, Melville, Prince Patrick, Seymour, Southampton.**
Pseudephebe pubescens (L.) Choisy **Axel Heiberg, Baffin, Bylot, Devon, Ellef Ringnes, Ellesmere, Meighen, Melville, Prince Patrick, Southampton.**
Psora decipiens (Hedwig) Hoffm. **Baffin, Banks, Bathurst, Bylot, Ellesmere, Somerset, Southampton.**
Psora rubiformis (Ach.) Hooker **Axel Heiberg, Baffin, Banks, Bylot, Ellesmere.**
Psora tenuifolia Timdal Ellesmere.
Psora vallesiaca (Schaer.) Timdal **Bathurst.**
Psoroma hypnorum (Vahl) S. Gray **Baffin, Bylot, Devon, Ellesmere, Southampton.**

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TABLE 3: (cont'd)

Pyrenopsis pulvinata (Schaer.) Th. Fr. (*Euopsis pulvinata*) (Schaer.) Nyl. **Devon.**
Rhizocarpon badioatrum (Floerke ex Spreng.) Th. Fr. **Axel Heiberg, Baffin, Bylot.**
Rhizocarpon chioneum (Norman) Th. Fr. **Baffin, Cornwallis, Devon, Prince of Wales, Victoria.**
Rhizocarpon concentricum (Davies) Beltr. **Baffin.**
Rhizocarpon copelandii (Koerb.) Th. Fr. **Baffin, Bylot, Devon, Ellef Ringnes, Ellesmere.**
Rhizocarpon crystalligenum Lynge **Baffin, Banks, Bylot, Devon.**
Rhizocarpon disporum (Naeg. ex Hepp) Muel. Arg. **Akpatok, Axel Heiberg, Baffin, Banks, Bathurst, Bylot, Devon, Ellesmere, Igloolik, Prince Patrick, Southampton.**
Rhizocarpon distinctum Th. Fr. **Baffin, Ellesmere.**
Rhizocarpon eupetraeum (Nyl.) Arn. **Baffin.**
Rhizocarpon expallescens Th. Fr. **Baffin.**
Rhizocarpon geographicum (L.) DC. **Akpatok, Axel Heiberg, Baffin, Banks, Bathurst, Bylot, Ellef Ringnes, Igloolik, Melville, Prince Patrick, Somerset, Southampton, Victoria.**
Rhizocarpon grande (Floerke ex Flotow) Arn. **Baffin, Ellesmere, Prince Patrick, Winter.**
Rhizocarpon hochstetteri (Koerb.) Vainio **Baffin, Devon, Ellef Ringnes.**
Rhizocarpon inarense (Vainio) Vainio **Baffin, Bathurst.**
Rhizocarpon intermediellum Raes. **Baffin, Bathurst, Cornwallis.**
Rhizocarpon jemtlandicum Lynge **Baffin, Devon, Victoria.**
Rhizocarpon macrosporum Raes. **Prince Patrick.**
Rhizocarpon norvegicum Raes. **Axel Heiberg, Ellesmere.**
Rhizocarpon pusillum Runem. **Axel Heiberg, Bylot, Ellesmere.**
Rhizocarpon rittokense (Hellbom) Th. Fr. **Baffin, Devon.**
Rhizocarpon subtile Runem. **Axel Heiberg, Ellesmere.**
Rhizocarpon superficiale (Schaer.) Vainio **Axel Heiberg, Baffin, Banks, Bathurst, Bylot, Cornwallis, Ellesmere, Prince Patrick, Winter.**
Rhizocarpon umbilicatum (Ram.) Flagey **Bathurst, Ellesmere, Southampton.**
Rhizoplaca chrysoleuca (Sm.) Poelt **Baffin.**
Rhizoplaca melanophthalma (Ram. in Lam. & DC.) Leuck. & Poelt in Leuck. Poelt & Hanel **Akpatok, Axel Heiberg, Baffin, Banks, Bathurst, Ellesmere.**
Rinodina archaea (Ach.) Arn. **Baffin, Ellesmere.**
Rinodina bischoffii (Hepp) Mass. **Baffin, Devon.**
Rinodina calcigena (Th. Fr.) Lynge **Axel Heiberg, Baffin, Bathurst, Devon, Ellesmere.**
Rinodina mniaraea (Ach.) Koerb. **Akpatok, Baffin.**

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TABLE 3: (cont'd)

Rinodina roscida (Sommerf.) Arn. **Baffin, Banks, Bathurst, Boothia Peninsula, Bylot, Devon, Ellesmere, Somerset, Southampton, Victoria.**
Rinodina turfacea (Wahlenb.) Koerb. **Axel Heiberg, Baffin, Bathurst, Boothia Peninsula, Bylot, Ellesmere, Prince Patrick, Somerset.**
Sagiolechia protuberans (Ach.) Mass. **Bathurst.**
Sagiolechia rhexoblephara (Nyl.) Zahlbr. **Baffin.**
Schaereria tenebrosa (Flotow) Hertel & Poelt **Ellesmere.**
Siphula ceratites (Wahlenb.) Fr. **Baffin, Devon.**
Solorina bispora Nyl. **Axel Heiberg, Baffin, Bathurst, Cornwallis, Ellesmere, Somerset, Southampton, Victoria.**
Solorina crocea (L.) Ach. **Axel Heiberg, Baffin, Bylot, Ellef Ringnes, Melville, Prince Patrick.**
Solorina octospora (Arn.) Arn. **Baffin, Bylot.**
Solorina saccata (L.) Ach. **Axel Heiberg, Baffin, Bylot, Southampton.**
Solorina spongiosa (Ach.) Anzi **Banks, Devon, Ellesmere, Southampton, Victoria.**
Sphaerophorus fragilis (L.) Pers. **Axel Heiberg, Baffin, Bylot, Southampton.**
Sphaerophorus globosus (Huds.) Vainio **Baffin, Bylot, Devon, Ellef Ringnes, Ellesmere, Lougheed, Melville, Prince Patrick, Seymour, Southampton.**
Sporastatia polyspora (Nyl.) Grumm. **Baffin, Bathurst, Ellesmere, Winter.**
Sporastatia testudinea (Ach.) Mass. **Akpatok, Axel Heiberg, Baffin, Banks, Bathurst, Bylot, Cornwallis, Melville, Prince Patrick, Victoria, Winter.**
Staurothele clopima Th. Fr. **Axel Heiberg, Baffin, Bathurst.**
Staurothele fuscocuprea (Nyl.) Zschacke **Akpatok, Bathurst, Southampton.**
Staurothele perradiata Lynge **Banks, Bylot, Ellesmere, Victoria.**
Stereocaulon alpinum Laur. ex. Funck **Axel Heiberg, Banks, Bylot, Devon, Ellef Ringnes, Ellesmere, Prince Patrick, Somerset, Southampton, Victoria.**
Stereocaulon arcticum Lynge **Baffin, Bylot, Ellesmere.**
Stereocaulon arenarium (Savicz) Lamb **Axel Heiberg, Baffin, Bylot.**
Stereocaulon botryosum Ach. **Baffin, Bylot, Devon, Ellef Ringnes, Ellesmere.**
Stereocaulon condensatum Hoffm. **Baffin, Bylot, Ellef Ringnes.**
Stereocaulon coniophyllum Lamb **Baffin, Bylot.**
Stereocaulon glareosum (Savicz) Magn. **Axel Heiberg, Baffin, Bylot, Cornwallis, Melville, Victoria.**
Stereocaulon incrustatum Floerke **Ellef Ringnes.**
Stereocaulon paschale (L.) Hoffm. **Axel Heiberg, Baffin, Cornwall, Ellesmere, "South Borden" (Mackenzie King** - see previous comment), **Southampton.**
Stereocaulon rivulorum Magn. **Amund Ringnes, Axel Heiberg, Baffin, Bylot, Devon, Ellesmere, Prince Patrick, Southampton.**
Stereocaulon symphycheilum Lamb **Bylot.**

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TABLE 3: (cont'd)

Stereocaulon tomentosum Fr. **Baffin.**

Stereocaulon vesuvianum Pers. **Baffin.**

Sticta arctica Degel. **Baffin, Bylot, Southampton.**

Teloschistes arcticus Zahlbr. **Banks, Melville** (and mainland on **Cape Parry**).

Tephromela algaea (Sommerf.) Hertel & Rambold **Baffin.**

Tephromela armeniaca (DC in Lam. & DC.) Hertel **Axel Heiberg, Baffin, Banks, Bylot, Devon, Prince Patrick.**

Tephromela atra (Huds.) Hafellner **Baffin, Devon, Prince Patrick.**

Thamnolia subuliformis (Ehrh.) W. Culb. **Axel Heiberg, Baffin, Banks, Boothia Peninsula, Bylot, Cornwallis, Devon, Ellesmere, Melville, Somerset, "South Borden" (Mackenzie King), Southampton, Victoria.**

Thamnolia vermicularis (Swarz) Ach. ex. Schaer. **Baffin, Banks, Bathurst, Bylot, Ellesmere, Southampton.**

Thelidium minutulum Koerb. **Baffin.**

Thelocarpon epibolum Nyl. **Axel Heiberg.**

Toninia caeruleonigricans (Lightf.) Th. Fr. **Axel Heiberg, Baffin, Cornwallis, Ellesmere, Somerset.**

Toninia lobulata (Sommerf.) Lynge **Baffin, Bathurst, Devon, Ellesmere.**

Toninia squalida (Schleicher ex Ach.) Mass. **Baffin.**

Toninia tristis (Th. Fr.) Th. Fr. **Axel Heiberg.**

Trapelia coarctata (Sm.) Choisy in Werner **Axel Heiberg.**

Trapeliopsis granulosa (Hoffm.) Lumbsch **Prince Patrick.**

Umbilicaria aprina Nyl. **Baffin.**

Umbilicaria arctica (Ach.) Nyl. **Bathurst, Bylot, Devon, Ellesmere, Southampton.**

Umbilicaria cylindrica (L.) Del. ex Duby **Baffin, Boothia Peninsula, Cornwallis, Vansittart.**

Umbilicaria deusta (L.) Baumg. **Baffin, Bylot.**

Umbilicaria havasii Llano **Baffin, Devon, Nottingham, Southampton.**

Umbilicaria hyperborea (Ach.) Hoffm. **Axel Heiberg, Baffin, Bylot, Devon, Ellesmere, Melville, Prince Patrick, Somerset, Southampton, Victoria.**

Umbilicaria proboscidea (L.) Schrader **Axel Heiberg, Baffin, Bathurst, Boothia Peninsula, Bylot, Devon, Ellef Ringnes, Prince Patrick, Southampton.**

Umbilicaria torrefacta (Lightf.) Schrader **Baffin, Bylot, Devon, Southampton.**

Umbilicaria vellea (L.) Ach. **Baffin, Bylot, Devon, Southampton.**

Usnea sphacelata R. Br. **Axel Heiberg, Baffin, Eglinton, Ellesmere, Melville, Prince Patrick, Seymour.**

Verrucaria aethiobola Wahlenb. in Ach. **Bathurst.**

Verrucaria arctica Lynge **Axel Heiberg, Baffin, Banks, Bathurst, Ellesmere, Victoria.**

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TABLE 3: (concl.)

Verrucaria ceuthocarpa Wahlenb. **Baffin.**

Verrucaria devergens Nyl. **Devon, Southampton.**

Verrucaria deversa Vainio **Banks, Bathurst, Cornwallis, Devon, Ellesmere, Somerset.**

Verrucaria margacea (Wahlenb. in Ach.) Wahlenb. **Baffin, Ellesmere.**

Verrucaria maura Wahlenb. in Ach. **Ellesmere.**

Verrucaria muralis Ach. **Bathurst.**

Verrucaria nigrescens Pers. **Baffin, Banks, Bathurst, Devon, Victoria.**

Verrucaria rupestris Schrader **Baffin, Bathurst, Somerset.**

Vestergrenopsis isidiata (Degel.) Dahl **Baffin, Devon.**

Xanthoria candelaria (L.) Th. Fr. **Baffin, Bathurst, Bylot, Cornwallis, Devon, Ellesmere.**

Xanthoria elegans (Link.) Th. Fr. **Axel Heiberg, Baffin, Banks, Bathurst, Devon, Ellesmere, Melville, Prince of Wales, Prince Patrick, Seymour, Somerset, Southampton, Victoria.**

Xanthoria sorediata (Vainio) Poelt. **Baffin, Bylot, Coats, Victoria.**

Illustrated by Brenda Carter

BIOCLIMATIC ZONES IN THE CANADIAN ARCTIC ARCHIPELAGO

S.A. Edlund[1]

Abstract: Woody plants may be as useful as bioclimatic indicators in the Arctic as trees are in the boreal forest. Northern Canada is divided into seven zones based on common growth-forms of woody plants on mesic soils. Zonal limits coincide remarkably well with mean July isotherms.

All five arctic zones occur in the Canadian Arctic Archipelago. The Low, Erect Shrub Zone roughly coincides with 7° to 10°C mean July isotherms. Many shrub species in this zone reach heights of 25 cm to more than 1 m, with densities ranging from nearly continuous canopies to isolated thickets. Tree-sized deciduous shrubs locally occur in this zone as well. The Dwarfed and Prostrate Shrub Zone roughly coincides with 5° to 7°C mean July isotherms. Woody species capable of low, erect growth are present but dwarfed (less than 25 cm high), and their importance in communities is greatly reduced. Naturally prostrate species such as Salix arctica and Dryas integrifolia are the dominant shrubs. The Prostrate Shrub Zone roughly coincides with 4-6°C means July isotherms. It, too, is dominated by Salix and Dryas, but lacks woody species capable of erect growth. The Prostrate Shrub-Herb Transition Zone roughly coincides with 3° to 4°C mean July isotherms. Herbaceous species are dominant, and prostrate shrubs are only sporadically present. The Herbaceous Zone, roughly coinciding with 1-3°C mean July isotherms, is dominated by herbs, and lacks woody plant species.

Résumé: Les plantes ligneuses peuvent être aussi utiles pour servir d'indicateurs bioclimatiques dans l'Arctique que les arbres dans la forêt boréale. Le Nord du Canada est divisé en sept zones selon les normes de croissance courantes des plantes ligneuses en sol mésique. Les limites de ces zones coïncident très bien avec les isothermes moyennes de juillet.

Les zones de l'Arctique, au nombre de cinq, sont toutes présentes dans l'archipel arctique canadien. La zone des sous-arbrisseaux érigés suit à peu près avec les isothermes de juillet de 7° à 10°C. Dans cette zone, un bon nombre d'espèces d'arbustes atteignent des hauteurs allant de 25 cm à plus d'un mètre, avec des densités variant des voûtes de verdure presque continues jusqu'aux bosquets isolés. Des arbustes feuillus de la taille d'un arbre se retrouvent également par endroits dans cette zone. Par ailleurs, la zone des sous-arbrisseaux et des arbrisseaux prostrés correspond approximativement avec les isothermes de juillet de 5° à 7°C. Des espèces ligneuses susceptibles de croissance lente et verticale y sont présentes, mais naines (moins de 25 cm de hauteur), et leur nombre est grandement réduit. Naturellement, les espèces procombantes telles Salix arctica et Dryas integrifolia sont des arbustes dominants. La zone des arbustes prostrés correspond approximativement aux isothermes de juillet de 4° à 6°C. Les Salix et les Dryas y prédominent également, mais il y manque des espèces ligneuses capables de croissance érigée. La zone de transition entre les arbustes prostrés et les herbes se situe approximativement aux isothermes de juillet de 3° à 4°C. Les espèces herbacées y sont prédominantes, tandis que les arbustes prostrés y sont dispersés. La zone des herbacées, qui coïncide à peu près avec les isothermes de juillet de 1° à 3°C, comprend surtout des herbes et pas d'espèces de plantes ligneuses.

INTRODUCTION

From the air much of the Arctic appears nearly devoid of vegetation because of the absence of trees and the shortness of arctic plants. This "barrens" image is reinforced in some areas of the Arctic, where soils derived from extremely alkaline or acidic bedrock do not permit plant growth. Most soils, however, support plant communities which in turn support major herbivore populations. Woody plants, including low, erect shrubs, to dwarfed, prostrate or matted shrubs, are major component of mesic plant communities over most of the Arctic.

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Geological Survey of Canada Contribution Number 10488

Two basic factors influence modern vascular-plant diversity and distribution: geology and climate. Many plant species and associations have preferences for, or intolerances to, chemical, textural and moisture variations of soils. Some species prefer weakly to moderately alkaline soils, while others do not tolerate such conditions. Similarly, some species have specific moisture requirements. For example, aquatic sedges require poorly-drained to saturated soil throughout most of the growing season. Other species can not tolerate such an abundance of moisture. Therefore, within a given area, each type of parent material has a suite of plant communities, each favouring a particular moisture regime. In the Arctic, where soils in summer are still underlain by permafrost and a few centimetres difference in elevation makes a great difference in the moisture availability, a mosaic - pattern of plant assemblages is characteristic (Polunin 1960; Bliss 1975, this volume).

Regional climate plays a large role in controlling the composition of arctic vegetation. Climate affects the diversity, density, productivity, and growth-forms of the vascular plants for any given type of substrate by controlling the temperature, length of the thaw-season, variations in precipitation, and intensity and duration of cloud-cover.

Summer warmth has the greatest influence on vegetation diversity (Young 1971; Rannie 1985). This control is best expressed as summations of total warmth such as Melting Degree-Days or Growing Degree-Days. Such data, however, are generally available only for the sparse network of northern weather stations (Atmospheric Environment Service 1982). The most readily available and widespread measure of summer warmth is the mean temperature for July, the warmest month (Figure 1).

In the Canadian Arctic, mean July isotherms grade northward from roughly 10°C near treeline to 1°C along the northwestern rim of the Queen Elizabeth Islands. This decline is not a simple, linear, latitudinal progression but a complex pattern reflecting the interaction between solar radiation received, characteristics of the dominant air-mass, topography, and amount of open water surrounding the islands during the summer (Edlund 1983A, 1986A).

On a global scale, the Arctic generally has been treated as a unit, even though this circumpolar ecosystem spans up to 31° of latitude. There are, however, several broad subdivisions of the North American Arctic ecosystem. Polunin (1951, 1960; Energy, Mines and Resources Canada 1973) divided the Arctic into three regions, Low, Mid, and High Arctic, based primarily on the abundance of continuous ground-cover and species diversity.

FIGURE 1: Mean July Temperatures in northern Canada, derived from northern weather stations (Atmospheric Environment Service 1982), community records, and selected non-standard weather data collected by Polar Continental Shelf Project (after Edlund 1986A).

Young (1971) proposed a circumpolar classification of arctic vegetation based on the diversity of vascular plants. He created four zones north of treeline that reflect the progressive impoverishment of vegetation poleward. He suggested that the primary ecological factor involved is the amount of available summer warmth.

Bliss (1977, this volume) divides the Canadian Arctic into two major regions on the basis of density and continuity of vegetation-cover: Low Arctic, encompassing the continental region north of treeline and the southeastern corner of Baffin Island; and High Arctic, which includes all islands of the Canadian Arctic Archipelago, as well as Boothia and Melville peninsulas and Wager Plateau in northern Keewatin. He further subdivided the High Arctic into three zones (Babb and Bliss 1974): Polar Desert, Polar Semidesert, and a Complex,

including Polar Desert, Polar Semidesert, and sedge-meadows. All three High Arctic zones occur throughout the Arctic Islands, although the Complex is more prevalent in the more southerly sector of the islands.

Detailed regional maps of plant associations for some areas of Arctic Canada (Edlund 1980, 1982A,B,C, 1983B,C,D, 1987B) revealed several broad vegetation patterns that could not be explained satisfactorily by previous proposed subdivisions. Comparisons with climatic patterns, particularly summer-temperature patterns, revealed great similarities between major vegetation changes and degree of severity of the summer climate (Edlund 1983A, 1986A). Because of the names Low, Mid, and High Arctic have been applied to different areas by different authors, I have avoided their use in the units that are described here, even though in a few regions some boundaries are similar. The new zones, instead, are named for the dominant vascular plant growth - form on mesic terrain. Nomenclature for vascular plants follows that of Porsild and Cody (1980).

BIOCLIMATIC ZONES IN ARCTIC CANADA

Seven major bioclimatic zones are delineated in northern Canada (Figure 2). Two of these encompass the transition from treed terrain to tundra. The other five are zones of the "true" or treeless Arctic. These zones are characterized by plant habitat and number of vascular-plant species and the roughly coincident mean July isotherms. They should not be interpreted directly as physiologically-significant temperatures, but rather as relative indicators of regional warmth.

Regional diversity within the seven bioclimatic zones was calculated by overlaying the Canada-wide zones on individual species range maps (Porsild 1964; Porsild and Cody 1980). Recent range extensions are also included. Total flora of a zone was compiled, irrespective of the chemistry, or drainage characteristics of soils. As Young (1971) and Rannie (1985) found, diversity of vascular plants decreases dramatically through the zones with decreasing summer temperatures. The diversity of both woody species and of species associated with wetlands and pond environments drops sharply, particularly where mean July temperatures drop below 7°C, whereas total diversity declines more gradually (Figure 3). Perennial

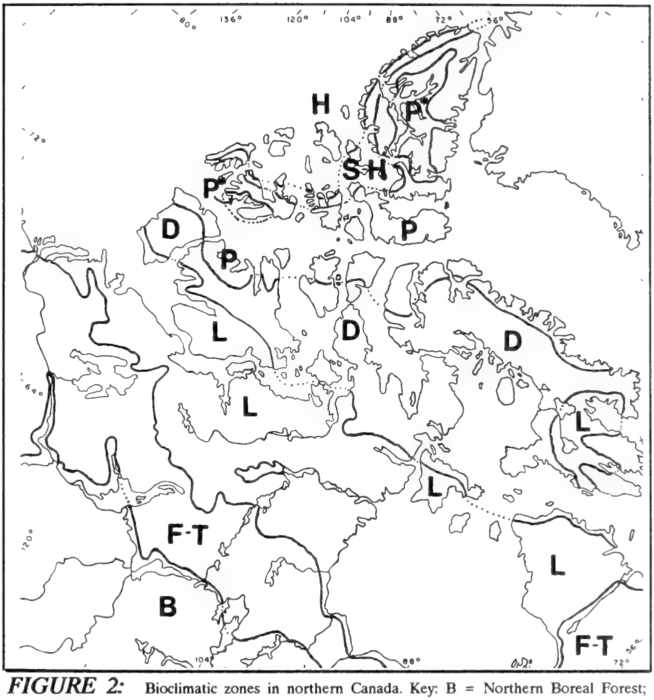

FIGURE 2: Bioclimatic zones in northern Canada. Key: B = Northern Boreal Forest; F-T = Boreal Forest-Tundra Transition Zone; L = Low, Erect Shrub Zone; D = Dwarfed and Prostrate Shrub Zone; P = Prostrate Shrub Zone; P* = Enriched Prostrate Shrub Zone; S-H = Prostrate Shrub-Herb Transition Zone; H = Herb Zone.

herbaceous species make up the largest number of taxa in all zones. Annuals are rare in the Arctic, and biennials are few and generally restricted to the warmest zones.

The seven major bioclimatic zones represent major shifts in vegetation patterns with increasingly severe summers. Although the zones were named to reflect changes in growth-forms and significance of woody species on mesic terrain, they also represent changes in density and diversity of herbaceous species in wetlands.

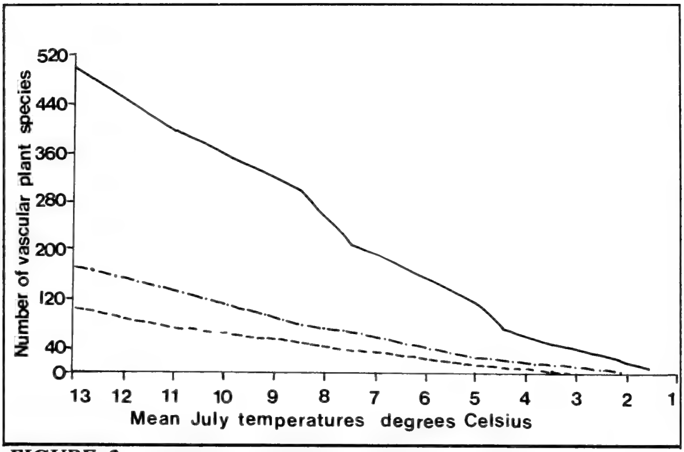

FIGURE 3: Diversity of vascular plants in the bioclimatic zones. Key: Solid line = Total number of vascular plant species; dashes and dots = number of wetland aquatic and emergent species; dashed line = number of woody species.

Northern Boreal Forest

The northern limit of the boreal forest, which coincides with the southernmost extent of the arctic biome, is one of the best known phytogeographic and bioclimatic boundaries. This limit roughly coincides with the mean position of the Arctic front in summer (Bryson 1966) and also with the 13°C mean July isotherm (Hare 1970). Compared to other northern zones, diversity is greatest within the Northern Boreal Forest Zone: over 500 vascular-plant species occur near the northern limit of the boreal forest, including more than 100 woody species and many temperate genera (Table 1) such as cherry (*Prunus*), currant (*Ribes*), mountain ash (*Sorbus*), dogwood (*Cornus*), silverberry (*Elaeagnus*), blueberry and bilberry (*Vaccinium*), and willow (*Salix*). The erect, single-trunked tree is the dominant vascular plant growth-form in this zone.

Near the northern forest-limit this continuous coniferous forest, confined to the northern mainland of Canada, is dominated by spruce (*Picea*). Other conifers such as larch (*Larix*),

TABLE 1: INDICATOR SHRUBS IN THE SEVEN NORTHERN BIOCLIMATIC ZONES AND CORRESPONDING MEAN JULY ISOTHERMS.

VEGETATION ZONE	MEAN JULY ISOTHERM °C	MAJOR WOODY SPECIES	INDICATOR SHRUBS AND TREES REACHING THEIR NORTHERN LIMITS WITHIN THE ZONE
NORTHERN BOREAL FOREST ZONE	13+	*Picea mariana* (Mill.) B.S.P. *Picea glauca* (Moench) Voss *Larix laricina* (DuRoi) Koch *Pinus banksiana* Lamb. *Betula papyrifera* Marsh *Populus balsamifera* L.	*Cornus canadensis* L. *Cornus stolonifera* Michx. *Elaeagnus commutata* Bernh. *Juniperus horizontalis* Moench *Prunus pennsylvanica* L. *Ribes glandulosum* Grauer *Ribes lacustre* (Pers.) Poir. *Salix barrattiana* Hook. *Salix interior* Rowlee *Salix lasiandra* Benth. *Salix padophylla* Rydb. *Salix scouleriana* Barratt *Salix serrissima* (Bailey) Fern. *Sorbus scopulina* Greene *Vaccinium caespitosum* Michx. *Vaccinium myrtilloides* Michx.
FOREST-TUNDRA TRANSITION ZONE	10-13	*Picea mariana* (Mill.) B.S.P. *Picea glauca* (Moench) Voss *Alnus crispa* (Ait.) Pursh *Betula glandulosa* Michx. *Cassiope tetragona* (L.) D.Don erect *Rhododendron lapponicum* (L.) Wahlenb. *Salix alaxensis* (Anderss.) Cov. *Salix bebbiana* Sarg. *Salix lanata* L. ssp. *calcicola* (Fern. & Weath.) Hult. *Salix lanata* L. ssp. *richardsonii* (Hook.) Skvortsov *Salix planifolia* Pursh	*Amelanchier alnifolia* Nutt. *Arctostaphylos uva-ursi* (L.) Spreng. *Betula occidentalis* Hook. *Betula papyrifera* Marsh *Betula pumila* L. *Chamaedaphne calyculata* (L.) Moench *Juniperus communis* L. *Kalmia polifolia* Wang. *Larix laricina* (DuRoi) Koch *Ledum groenlandicum* Oeder *Linnaea borealis* L.[1] *Myrica gale* L. *Oxycoccus microcarpus* Turcz. *Populus balsamifera* L. *Populus tremuloides* Michx. *Potentilla fruticosa* L.[1] *Ribes hudsonianum* Richards. *Ribes triste* Pall. *Rosa acicularis* Lindl. *Rubus acaulis* Michx. *Rubus strigosus* Michx. *Salix arbusculoides* Anderss.[1]

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TABLE 1: (cont'd)

VEGETATION ZONE	MEAN JULY ISOTHERM °C	MAJOR WOODY SPECIES	INDICATOR SHRUBS AND TREES REACHING THEIR NORTHERN LIMITS WITHIN THE ZONE
			Salix brachycarpa Nutt. *Salix interior* Rowlee *Salix myrtillifolia* Anderss. *Salix pedicellaris* Pursh *Salix pyrifolia* Anderss. *Shepherdia canadensis* (L.) Nutt. *Vibernum edule* (Michx.) Raf.
LOW, ERECT SHRUB ZONE	7-10	*Cassiope tetragona* (L.) D.Don *Dryas integrifolia* M. Vahl *Ledum decumbens* (Ait.) Lodd. *Salix arctica* Pall. *Salix lanata* ssp. *richardsonii* (Hook.) Skvortsov	krummholz of *Picea mariana* (Mill.) B.S.P. *Alnus crispa* (Ait.) Pursh *Andromeda polifolia* L. *Betula glandulosa* Michx. *Loiseleuria procumbens* (L.) Desv. *Phyllodoce coerulea* (L.) Bab. *Rubus chamaemorus* L. *Salix alaxensis* (Anderss.) Cov.[1] *Salix fullertonensis* Schneid. *Salix glauca* L. *Salix niphoclada* Rydb.[1] *Salix planifolia* Pursh *Salix pulchra* Cham.
DWARFED AND PROSTRATE SHRUB TUNDRA	5-7	*Cassiope tetragona* (L.) D.Don *Dryas integrifolia* M. Vahl *Salix arctica* Pall.	*Arctostaphylos alpina* (L.) Spreng. *Arctostaphylos rubra* (Rehd.) & Wils.) Fern. *Diapensia lapponica* L. *Empetrum nigrum* L.[1] *Ledum decumbens* (Ait.) Lodd *Rhododendron lapponicum* (L.) Wahlenb.[1] *Salix arctophila* Cockerell *Salix cordifolia* Pursh *Salix herbacea* L.[1] *Salix lanata* ssp. *richardsonii* (Hook.) Skvortsov *Salix polaris* Wahlenb.[1] *Salix reticulata* L.[1] *Vaccinium uliginosum* L.[1] *Vaccinium vitis-idaea* L.

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TABLE 1: (cont'd)

VEGETATION ZONE	MEAN JULY ISOTHERM °C	MAJOR WOODY SPECIES	INDICATOR SHRUBS AND TREES REACHING THEIR NORTHERN LIMITS WITHIN THE ZONE
PROSTRATE SHRUB ZONE	4-6	*Dryas integrifolia* M. Vahl *Salix arctica* Pall.	*Cassiope tetragona* (L.) D.Don
PROSTRATE SHRUB-HERB TRANSITION ZONE	3-4	none	*Dryas integrifolia* M. Vahl *Salix arctica* Pall.
HERBACEOUS ZONE	1-3	none	none

[1] Species found under exceptionally favourable local conditions in the zone directly northward.

fir (*Abies*) and pine (*Pinus*) are also present (Rowe 1972; Ritchie 1984; Richard 1987). Tall deciduous shrubs and small trees of birch (*Betula*), alder (*Alnus*), aspen (*Populus*), and willow (*Salix*) occur in this zone too (Gill 1973; Gilbert and Payette 1982; Ritchie 1984), often as successional species in opening or disturbed terrain such as river margins. The coniferous shrub common juniper (*Juniperus communis*) also occurs this zone.

Wetlands, dominated by sedges, contain over 170 wetland (growing in poorly-drained soils), emergent (growing with lower stems partially submerged), and aquatic (vegetative growth totally submerged) species. A number of woody species and herbs are present on mounds of peat, which afford slightly better-drained conditions.

<u>**Forest-Tundra Transition Zone**</u>

In regions where mean July temperatures fall below 13°C, the continuous forest is absent. The tree growth-form persists, however, and woody plants continue to dominate all but the wettest terrain. Between 13° and 12°C, trees commonly occur in an open formation; between 12° and 10°C, trees are generally restricted to favoured locations such as sunny slopes and sheltered, well-watered valley bottoms. Low, erect shrubs, 25-100 cm high, occur in many parts of this zone both as individual clumps and as dense thickets on moderately to imperfectly-drained materials, although lichens are the common ground-cover on some

areas of the Canadian Shield. Prostrate (low and sprawling) shrubs are more common on thin, well-drained soils and on more exposed sites. Multi-branched, small tree-sized deciduous shrubs such as *Salix* and *Alnus* occur on floodplains and disturbed terrain. The total vascular plant diversity is greater than 400 species, including at least 75 woody species.

Wetlands contain about 130 wetland, aquatic, and emergent species, (still rich by northern standards), as well as a variety of sedges, shrubs and herbs. Sedges are still the dominant vascular plants.

Treeline, the northern limit of the coniferous tree growth-form and the northern limit of the Forest-Tundra Transition Zone, occurs on the continental mainland. Treeline does not occur on any of the Arctic Islands, however it comes close to the northern continental margin near the head of Horton and Coppermine rivers and the Mackenzie Delta. It coincides roughly with the 10°C mean July isotherm (Nordenskjöld and Mecking 1928; Hare 1970). Many other, more temperate woody species include small, deciduous trees such as poplar (*Populus*), birch (*Betula*), *Alnus*, a few *Salix* species and serviceberry (*Amelanchier*), and shrubs such as northern rose (*Rosa acicularis*), shrubby cinquefoil (*Potentilla fruticosa*), bog laurel (*Kalmia polifolia*), sweet gale (*Myrica gale*), spirea (*Spirea beauverdiana*), soapberry (*Sherpherdia canadensis*), twin flower (*Linnaea borealis*), common Labrador tea (*Ledum groenlandicum*), cranberry (*Oxycoccus microcarpus*) and common bearberry (*Arctostaphylos uva-ursi*) (Table 1).

Low, Erect Shrub Zone

The best vegetated region of the "true" (treeless) Arctic occurs immediately north of treeline including: the northernmost mainland, southern Banks, Victoria, and Baffin islands, and the islands in Hudson and James bays. Mean July temperatures within this region range between 10° and 7°C. Over 300 vascular-plant species occur in this zone, of which more than 50 are woody. This is the arctic zone with the greatest vascular-plant density and diversity (Figure 3).

Conifers are generally absent, except near treeline, where the low shrub *Juniperus communis* and *Picea*, which locally occurs in a severely dwarfed, or "krummholz" growth-form (Figure 4), both may be found. Woody plants, particularly low, erect shrubs (25 cm to 1 m high or more), such as dwarf birch (*Betula glandulosa*) and *Salix*, as well as

FIGURE 4: Krummholz of Picea mariana, in the Coppermine River area, near treeline. Note also the size of dwarf birch (Betula glandulosa) in the foreground.

FIGURE 5: Low, erect Salix lanata var. richardsonii on Victoria Island. The low thickets are 25-50 cm high.

ericaceous species such as arctic white heather (*Cassiope tetragona*) and northern Labrador tea (*Ledum decumbens*) are dominant. In the warmest sectors, the low shrub-thicket canopy (0.5-1.0 m high) can be nearly continuous on sheltered, well-watered slopes. In the cooler sectors, the dense low-shrub thickets (25-50 cm high) are restricted to more sheltered locations (Figure 5). Exposed terrain and thin soils are dominated by prostrate shrubs, such as arctic avens (*Dryas integrifolia*), and arctic willow (*Salix arctica*), or low ericaceous species (Table 1).

Tree-sized (2-7 m high) felt leaf willows (*Salix alaxensis*) locally occur in this zone, generally on floodplains near the edges of deep channels and in sheltered locations (Maycock and Matthews 1966; Edlund and Egginton 1984). Away from stream margins, this same willow species commonly adopts the more usual low, erect growth-form.

Wetlands contain 75 wetland, aquatic, and emergent species. Sedges still dominate and low, erect shrubs and a variety of herbs often occur on slightly better-drained terrain within the wetlands. The most continuous coverage of tussock-cotton grass tundra (mainly *Eriophorum vaginatum*), primarily found on extensive fine-grained sediments of coastal lowlands, is also found in this zone.

The Low, Erect Shrub Zone marks the northern limit of many common arctic-shrub species such as dwarf birches (*Betula glandulosa* and *B. nana*), green alder (*Alnus crispa*), andromeda (*Andromeda polifolia*), alpine azalea (*Loiseleuria procumbens*), mountain heather (*Phyllodoce coerulea*), and cloudberry (*Rubus chamaemorus*).

Dwarfed and Prostrate Shrub Zone

In regions with mean July temperatures between 7° and 5°C, the low, erect shrub growth-form is absent, although species capable of erect growth, such as *Salix alaxensis*, *Salix lanata* var. *richardsonii*, and *S. niphoclada* still occur. The growth-form of these species is stunted (less than 25 cm high; Figure 6). These dwarfed species, generally restricted to sheltered, well-watered sites, are only a small part of the plant communities.

Mesic soils in the zone are usually dominated by genetically-dwarfed shrubs. One such species is the prostrate arctic willow (*Salix arctica*), whose branches sprawl along the ground. Its lateral extent can total a metre or more (Figure 7)! Another common species is the matted shrub *Dryas integrifolia*, which occurs abundantly on neutral to moderately alkaline soils. These two species are also present in more southerly zones, but are restricted to

FIGURE 6: Salix lanata var. richardsonii in its dwarfed "krummholz" form on Victoria Island. The trowel shows that this low thicket is less than 12 cm high.

FIGURE 7: Arctic willow (Salix arctica), the most common prostrate shrub in the Canadian Arctic Islands. Its branches can extend to a diameter of more than a metre.

thinner soils and more exposed terrain. Vascular plant species diversity in this zone ranges from 150 to 300 species, including 17 woody species.

Wetland communities, dominated by sedges, contain 35 wetland, aquatic and emergent species. Both dwarfed and prostrate shrub species are present on slightly better-drained hummocks. *Eriophorum* tussock-tundra may also occur, although its coverage is not as dense or extensive as it is in the Low, Erect Shrub Zone.

This zone occurs extensively in the southern tier of Arctic Islands, on the mainland on Boothia and Melville peninsulas, and on a strip along the northern coast of Ungava Peninsula. Its northern limit is south of Parry Channel. It generally marks the northern extent of shrub species capable of erect growth, including northern Labrador tea (*Ledum decumbens*), Lapland rosebay (*Rhododendron lapponicum*), several *Salix* species, a number of naturally prostrate ericaceous species and *Empetrum nigrum* (Table 1).

Prostrate Shrub Zone

In regions where mean July temperatures range between 6° and 4°C, the plant assemblages are generally similar to those in the Dwarfed and Prostrate Shrub-Tundra Zone, but shrubs capable of erect growth are absent. The woody species *Salix arctica* and *Dryas integrifolia* still dominate mesic terrain. On the whole, the flora of this zone is less diverse. Most obviously absent are Leguminosae (particularly *Oxytropis* and *Astragalus*), arctic fireweed (*Epilobium latifolium*), and many Compositae - particularly those with erect flowering stems such as *Senecio congestus, Petasites frigidus*, and *Arnica alpina*, as well as the more compact *Antennaria compacta, Chrysanthemum integrifolium, Crepis nana*, and *Erigeron* species. *Cassiope tetragona*, the hardiest heath species, is restricted to neutral to acid soils in the warmer sectors with mean July temperatures at least 5°C. Less obvious are decreases in numbers of grass and sedge species. Vascular-plant diversity ranges from 75 to 150 species, including 12 woody species.

Wetlands are still dominated by sedges, but their diversity is reduced to three common species, *Carex aquatilis* var. *stans, Eriophorum triste* and *E. scheuchzeri*. *Eriophorum* tussock-tundra does not occur in this zone, although the species itself may occur locally. Only 24 wetland, aquatic and emergent species occur in this zone. Grasses, particularly *Dupontia fisheri* and *Alopecurus alpinus*, are common associates in these wetlands, and may locally become dominant, particularly on bare mineral soils.

There are two widely separated areas within this zone where floral assemblages are exceptionally rich: western Melville Island and west-central Ellesmere Island (Edlund 1986B). These "enriched zones" resemble the Dwarfed and Prostrate Shrub Zone, except for the absence of species capable of erect shrub growth (e.g. *Salix alaxensis, S. lanata* and *S. niphoclada*). Mesic floras of western Melville Island locally include *Oxytropis, Astragalus*, and a variety of more southerly Compositae as well as *Epilobium latifolium*, although these species may have greatly stunted flowering-stalks (Edlund 1986B, 1987A,B).

The "enriched zone" of west-central Ellesmere Island is similarly enhanced (Bruggemann and Calder 1953; Brassard and Beschel 1968; Soper and Powell 1983; Bridgland and Gillett 1984). No Leguminosae are present, but six species of shrubs, (*Salix herbacea, S. polaris, S. reticulata, Rhododendron lapponicum, Vaccinium uliginosum* and *Empetrum nigrum*) are found in a few sites (Porsild 1964; Porsild and Cody 1980).

These disjunct enriched zones (Figure 2) roughly correspond to anomalously warm areas (Figure 1) where temperature ranges overlap with those of the Dwarfed and Prostrate Shrub Zone, with mean July temperatures of at least 5°C. These areas may represent outliers of the warmer Dwarfed and Prostrate Shrub Zone, since most other associated species thrive there. Low, erect shrub species may not have been dispersed into these areas.

These "enriched areas" also show enhanced growth and diversity in wetland, aquatic and emergent species. More southerly species such as *Carex membranacea, Hippuris vulgaris*, and *Ranunculus gmelini* occur in both areas, while *Arctophila fulva* and *Caltha palustris* occur only in southwestern Melville Island.

The Prostrate Shrub Zone extends from the south side of Parry Channel, well into the Queen Elizabeth Islands. The 4°C mean July isotherm roughly coincides with the northern limit of woody-plant dominance, and with the northern limit of sedge dominance in wetlands.

Prostrate Shrub-Herb Transition Zone

Woody plants are present but no longer dominant in regions with mean July temperatures below 4°C. They are replaced by herbs, generally those that were most common in plant communities in the Prostrate Shrub Zone to the south. This transition zone, bracketed by the 4° and 3°C mean July isotherms, contains between 35 and 75 vascular plant species, including only two woody species. *Salix arctica* and *Dryas integrifolia* are generally restricted to sunny, sheltered locations. The common growth-form of *Salix*

arctica is extremely compact (Figure 8).

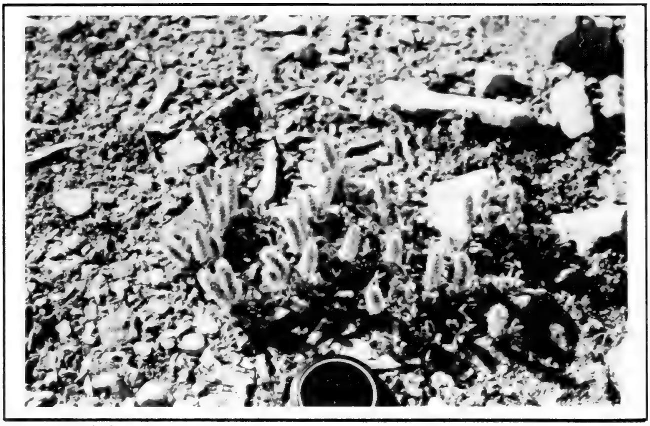

FIGURE 8: The compact form of Salix arctica near its northern limit on Melville Island. The branching extent is less than 10 cm.

A major change in composition also occurs in wetlands. There are only 11 wetland, aquatic and emergent species. Sedges, while present, are no longer dominant. Vascular wetland plants are restricted primarily to grasses, such as *Alopecurus alpinus* and *Dupontia fisheri*, as well as some herbs. Only a few emergent species such as *Pleuropogon sabinei* and *Ranunculus hyperboreus* survive in this zone.

This zone is found primarily in the north-central and northern Queen Elizabeth Islands. The 3°C mean July isotherm roughly coincides with both the northern limit of this zone and with the northern limit of the presence of woody plants. This boundary also marks the northern limit of sedges.

Herbaceous Zone

Vascular plant assemblages are entirely herbaceous in regions where mean July isotherms fall below 3°C. This zone is found in the northwestern and north-central Queen Elizabeth Islands and extends to their northern margins (Edlund 1980, 1983A). Neither woody plants, sedges, members of the Compositae nor aquatic or emergent species occur in this zone. The total vascular plant diversity is less than 35 species. There are no true wetland species in this zone; four vascular species grow on saturated soils, but these occur on somewhat drier habitats as well.

APPLICATIONS OF ARCTIC VEGETATION ZONATION

Few detailed paleoenvironmental reconstructions have been attempted north of treeline in Arctic Canada, perhaps because the tree growth-form is the most northerly well-known bioclimatic indicator. However, several arctic vegetation patterns can be roughly linked to mean July isotherms as in the northern boreal forest and treeline.

Many vascular-plant species show promise as bioclimatic indicators that can assist in extrapolating modern summer climate data into treeless regions where there are no climate records. This link can also assist in paleoenvironmental reconstructions in a treeless environment, for many plant macrofossils preserved in organic deposits and sediments are the same species that serve as bioclimatic indicators today.

Woody plants are one of the most useful bioclimatic indicators throughout the Arctic, even though the tree growth-form is absent. The presence of coniferous krummholz is, in itself, a useful indicator of climatic conditions close to those found near the coniferous treeline, roughly corresponding to the 10°C mean July isotherm. The small-tree growth-form of several deciduous shrubs, such as *Betula*, *Alnus* and *Salix* also indicates that treeline climatic conditions occur at least locally.

Where tree growth-forms are absent, treeline climatic conditions may also be indicated by the presence of several more temperate woody species such as: *Juniperus communis*, *Amelanchier alnifolia*, *Spirea beauverdiana*, *Myrica gale*, several *Ribes*, *Ledum groenlandicum*, *Rosa accicularis*, *Rubus strigosus*, *Potentilla fruticosa*, *Linnaea borealis*, and shrubby *Salix* species.

In the Arctic Islands the presence of shrubs with low, erect growth-forms (e.g. *Salix alaxensis*, *S. glauca*, *S. lanata*, *S. niphoclada*, *Ledum decumbens*, *Betula glandulosa*, and a variety of ericaceous species) indicates a climate comparable to the warmest sector of the Arctic - the denser and higher the thickets, the warmer the summer climate.

The trend of increasing restriction of low, erect thicket-growth to sheltered, well-watered places with decreasing temperatures (from 10° to 7°C) is similar to the pattern displayed by trees in the Forest-Tundra Transition Zone. The northern limit of low, erect shrubs roughly corresponds to the 7°C mean July isotherm, and is the southern Arctic equivalent of the northern forest limit.

The climatic dwarfing of willows, the deciduous equivalent of coniferous krummholz, is an indicator of regional mean July temperatures ranging from 7° to 5°C. The northern limit

of species capable of erect shrub-growth roughly corresponds to the 5°C mean July isotherm, and is the southern Arctic equivalent of treeline.

Prostrate shrubs thrive from the northern limit of coniferous forest. They are important, often dominant, species throughout most of the Canadian Arctic Archipelago. In regions with mean July temperatures above 5°C, the branches of *Salix arctica* may spread out to a metre or more. The diameter of *Salix arctica* clumps decreases dramatically as mean July temperatures decrease below 5°C. Prostrate and matted shrubs lose their dominance when regional mean July temperatures drop below 4°C. The northern limit of woody plant dominance (the northern Arctic equivalent of the northern forest-limit) roughly corresponds to the 4°C mean July isotherm. Prostrate and matted shrubs persist locally into regions cooler than 4°C, but their growth-forms are extremely compact. Clumps of *Salix arctica* may be no more than 10 cm in diameter. The northern limit of woody plants roughly corresponds to the 3°C mean July isotherm, which can be considered the northern Arctic equivalent of treeline.

Wetlands, too, have several obvious bioclimatic indicators. A great diversity of wetland, aquatic and emergent species suggests conditions that occur today in the warmest zones of the Arctic. The presence of extensive *Eriophorum* tussock-tundra suggests mean July temperatures of at least 5°C. The presence of low, erect shrubs in the tussock-tundra would indicate mean July temperatures of at least 7°C. The dominance of sedge species in wetlands indicates mean July temperatures of at least 4°C, and the mere presence of sedges indicates mean July temperatures of at least 3°C.

With further research we should be able to refine and discover more bioclimatic indicators.

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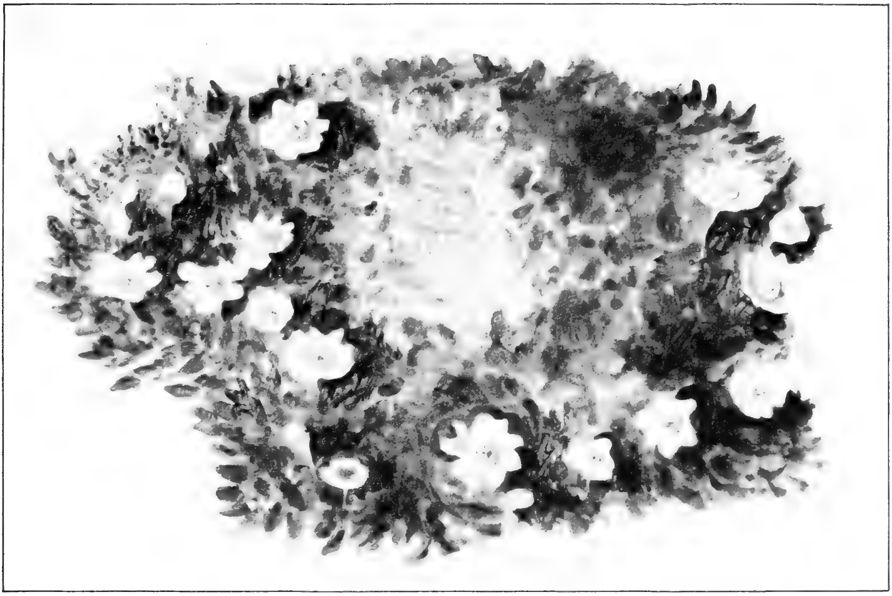

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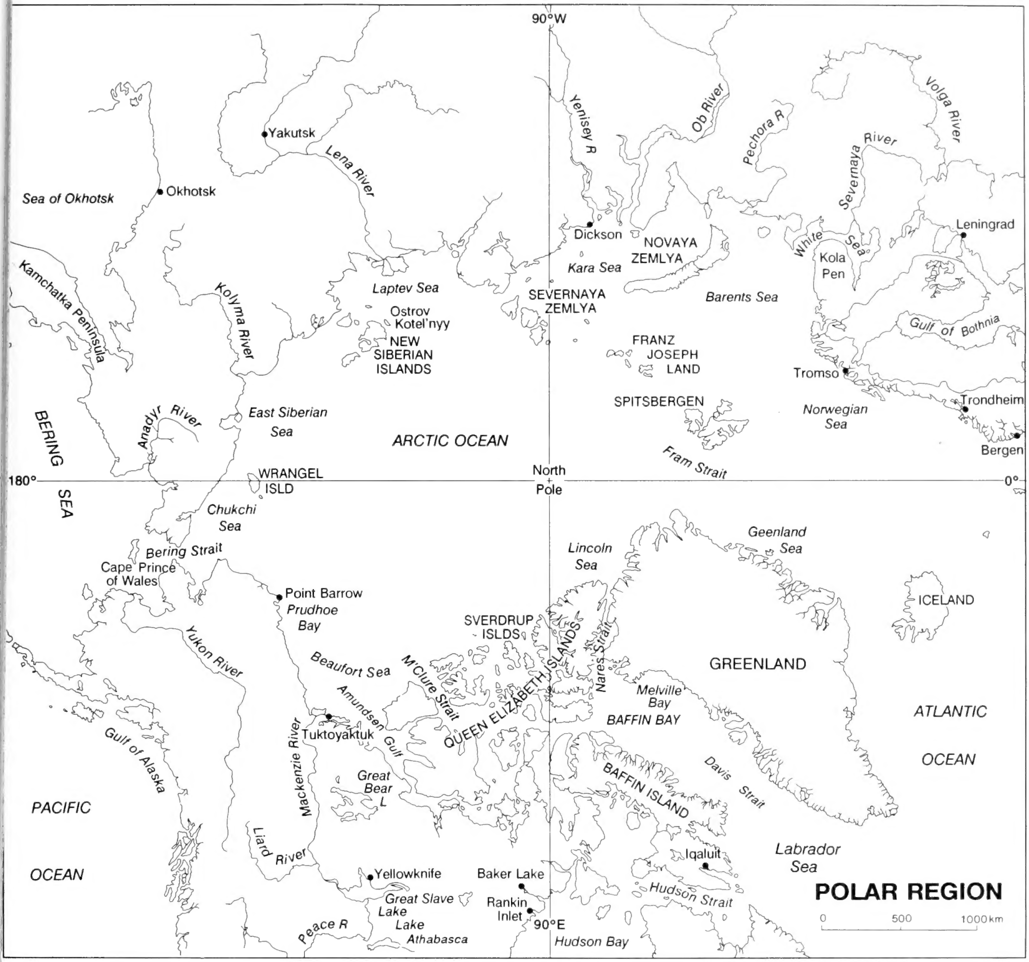

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